AD-A092 438 NAVAL RESEARCH LAB WASHINGTON DC F/G 10/2

RESULTS OF THE SOLAR CELL EXPERIMENTS ABOARD THE NTS-2 SATELLIT--ETC(U)

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UNCLASSIFIED NRL-MR-4372 NL

1 OF 1

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
NRL Memorandum Report 4372

2. GOVT ACCESSION NO.
AD-A092

3. RECIPIENT'S CATALOG NUMBER
438

4. TITLE (and Subtitle)
RESULTS OF THE SOLAR CELL EXPERIMENTS ABOARD THE NTS-2 SATELLITE AFTER 811 DAYS IN ORBIT.

5. TYPE OF REPORT & PERIOD COVERED
Interim report from 1 October 1978 to 30 September 1979

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Delores H. Walker

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Research Laboratory
Washington, D.C. 20375

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
62203A; USAF; 66-0415-0-0

11. CONTROLLING OFFICE NAME AND ADDRESS

12. REPORT DATE
November 13, 1980

13. NUMBER OF PAGES
44

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
1 Oct 78-30 Sep 79

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Solar cells
Space radiation
Solar cell coverslides
Satellite power systems
Radiation damage
I-V curve
NTS-2
Photovoltaic cells

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results obtained from the solar cell experiment aboard the NTS-2 satellite after 811 days in orbit. The objective of the solar cell experiment is to evaluate the performance and radiation hardness of state-of-the-art solar cells in the space environment. The experiment is comprised of fifteen (15) separate experimental modules each containing five 2 X 2 cm solar cells connected in series. The solar cell types include advanced state-of-the-art silicon solar cells such as the Comsat CNR cell, the Spectrolab Textured Helios Reflector cell, and the Solarex

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20. Abstract (Continued)

Vertical Junction cell. Also included for the first time in a flight experiment is the Hughes gallium-arsenide/gallium-aluminum-arsenide cell. There are also on board experiments to evaluate environmental effects on coverslip adhesives.

Telemetered data indicate a radiation environment in the 63 degree, 21,190 km circular orbit of NTS-2 only slightly harder than the predicted value for 1 MeV electron fluence equivalent calculated from space radiation models. Based on the NTS-2 data, the spacecraft main solar array of Spectrolab Helios cells will degrade 27 percent in maximum power over the three-year mission. Solar cell temperatures have reached 105 degrees C, providing the opportunity to look for moderate temperature annealing of radiation-induced damage in the gallium arsenide cells.

After more than 26 months in orbit, the loss in power ranged from 20.6 percent in the Spectrolab Textured Hybrid cell with FEP Teflon bonded coverslip to 52.1 percent in the Comsat textured cell without uv filter. These values do not include the following three solar cell modules which have ceased to function: (1) the Solarex space cell (exp. 8) which became open-circuited on the 69th day; (2) the Solarex vertical junction cell (exp. 7) which failed on day 720; and (3) the Spectrolab Textured Helios Reflector cell (exp. 9) which failed on day 783. The average value of solar simulator I_{sc} agrees to within 1.41 ± 0.99 percent of the value measured in space. The agreement between V_{oc} in space and solar simulator values was 1.24 ± 1.08 percent. The changes in the photovoltaic parameters of each of the experiments are summarized in the report.

CONTENTS

RESULTS OF THE SOLAR CELL EXPERIMENTS ABOARD
THE NTS-2 SATELLITE AFTER 811 DAYS IN ORBIT

Background

The Navigation Technology Satellite-Two (NTS-2) is the second of two developmental satellites which are technology prototypes for the NAVSTAR Global Positioning System (GPS). NAVSTAR GPS system is a 24 element constellation of satellites that will use passive ranging techniques combined with highly accurate clocks to provide extremely accurate navigation capability to ships, aircraft, ground forces and other users 24 hours a day, worldwide, in any kind of weather. The GPS satellites will occupy various positions in orbit affording extremely accurate three-dimensional navigational information, i.e., longitude, latitude, and altitude. NTS-2 was launched 23 June 1977 into a twelve-hour circular orbit 20,192 km high at an inclination of 63°.

The GPS satellites will derive electric power from solar cells. The system requirements demand a high level of reliability and sustained performance throughout the mission. The most damaging environmental factor in space for the solar array is particle radiation which adversely affects solar cells, leading to a reduction in the solar cell power output. Therefore, in order to predict the expected lifetime of a satellite mission, it is necessary to know quantitatively the effects of radiation on solar cells in space. Although numerous measurements of solar cells have been made in the laboratory,[1-10] it is a fact that solar cell behavior can only be accurately determined in the combined factors of the actual space environment.

The fifteen (15) solar cell experiments aboard NTS-2 are designed to compare initial space performance with prelaunch ground data, to measure degradation rates throughout the flight, and to determine the radiation resistance of several types of experimental and advanced design solar cells. These experiments will also answer questions that have arisen from the NTS-1[11-13] solar cell experiments, such as: the need for ultraviolet rejection filters in space solar cell systems, space qualification of electrostatic bonding techniques for solar cell coverslips and the improved efficiency to be realized from the use of textured cell surfaces. In addition, a gallium arsenide (GaAlAs/GaAs) solar cell module is being flight tested. Each of the fifteen separate experiments consists of an array of five 2 cm x 2 cm state-of-the-art solar cells with all experiments linked to an electronics package which measures the entire photovoltaic I-V curve of each experiment in sequence every two minutes.

Requirements

This is the second annual report on the NTS-2 solar cell flight experiments and covers the period from 1 October 1978 through 30 September 1979 as requested by the program monitor.

Manuscript submitted September 3, 1980.

The major goals of the past year's work at the Naval Research Laboratory were to reduce, correct, and analyze the data each month to provide a history of the temperature, open-circuit voltage, short-circuit current and maximum power for all fifteen experiments. These goals have been achieved. Some of the results have been forwarded in interim reports. The results of the NTS-2 solar cell flight experiments from launch through 30 September 1979 are summarized in detail in this report.

Experimental Results

This report covers the analysis of data from the fifteen (15) solar cell experiments aboard the NTS-2 satellite through 30 September 1979. To date thirty-six selected revolutions have been analyzed. This period covers 811 days in orbit. Day one is reckoned as 7 July 1977 when the solar power paddles were deployed, exposing the solar cell experiments to solar illumination and to the total radiation environment. Until that time, the solar cell experiments had been covered by the main array paddles that were held in the wrap-around launch configuration as shown in Figure 1a. That arrangement provided an effective shielding thickness of 40 mils of aluminum (0.274 gm/cm^2). The satellite is rotated around the appropriate axis, as needed, to maximize the solar cell paddle exposure to the sun. Because of the location of the experiments, this maneuver also maximizes the exposure of the experiments to the sun. Figure 1b shows the location of the panels on the spacecraft.

The current-voltage characteristics of the solar cell arrays are telemetered in real time as the satellite passes over the tracking station at Blossom Point, Maryland. The electronic circuit measures the I-V curve for each module in sequence reading out current-voltage values for evenly-spaced points from I_{SC} to V_{OC}. A typical I-V curve showing the number of points obtained is shown in Figure 2. Each cell module is short-circuited except when it is being stepped through the I-V curve. Data were obtained from the experiments within 6 hours of deployment. During the first recorded revolution (Rev. 31) the panel temperature measured close to 60°C.

Temperatures are monitored at the rear surface of four cells by means of three thermistors and one wire resistance thermometer. The thermistors are accurate to within $\pm$ 3°C up to 100°, and the wire thermometer is accurate to within $\pm$ 2 degrees C to above 120°C. The experimental panels are continuously illuminated by the sun (except during the biannual eclipse season of 25 days) by virtue of the sun orientation requirements of the main array.

Since day 1, the panel temperatures have gradually increased to higher than 100°C. Since September 1978, the temperatures have remained quite stable. The solar cells on panel 1 maintain a temperature around 105°C while the temperature of the solar cells on panel 2 is near 100°C. The average temperatures of both solar cell panels versus days in orbit are shown in Figure 3. This temperature rise in excess of 20 degrees higher than predicted has been attributed to the ultraviolet and particle radiation

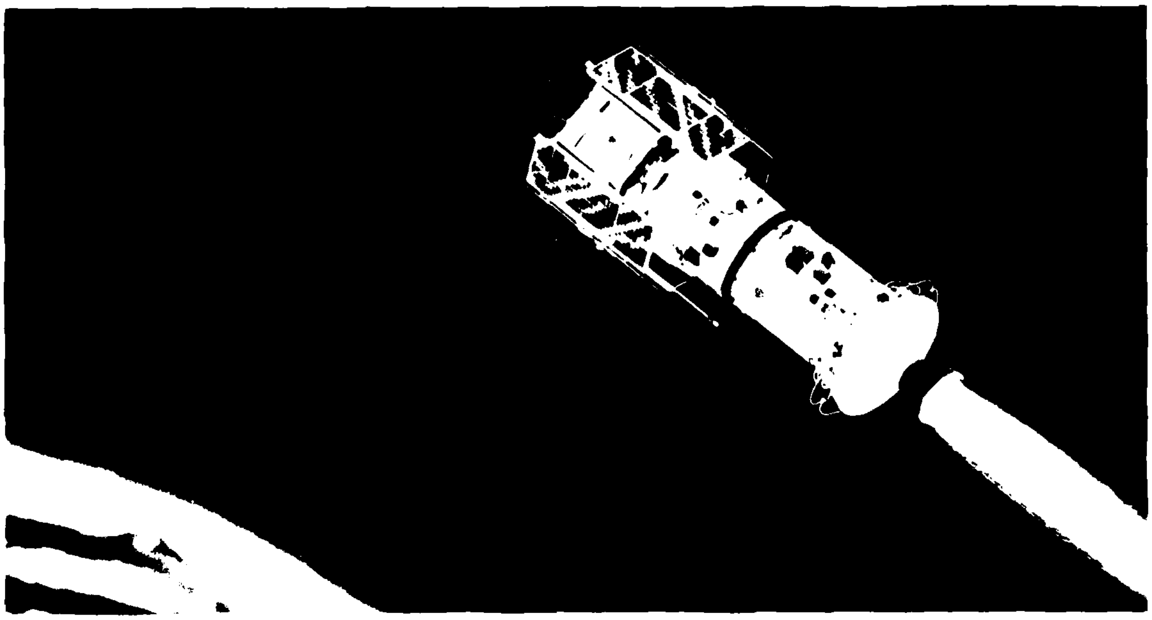

Figure 1a The NTS-2 satellite with solar paddles folded during launch

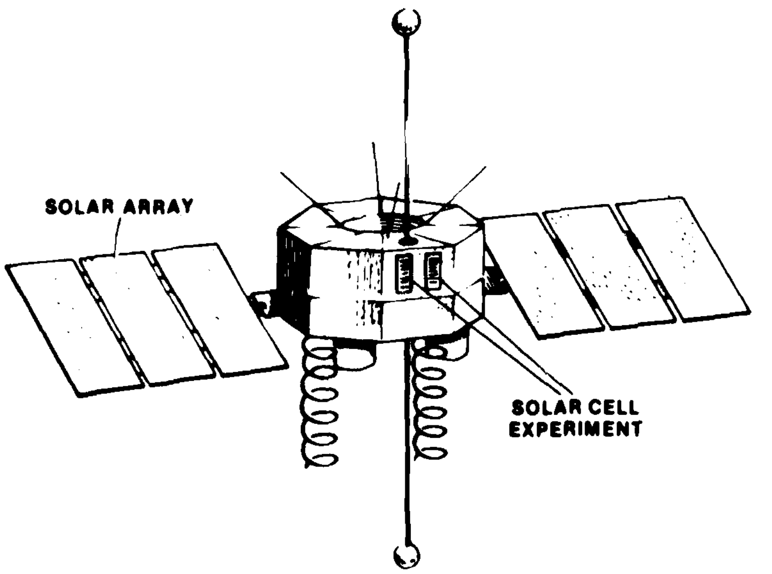

Figure 1b The NTS-2 satellite with solar arrays deployed and showing the location of the two solar cell experiment panels

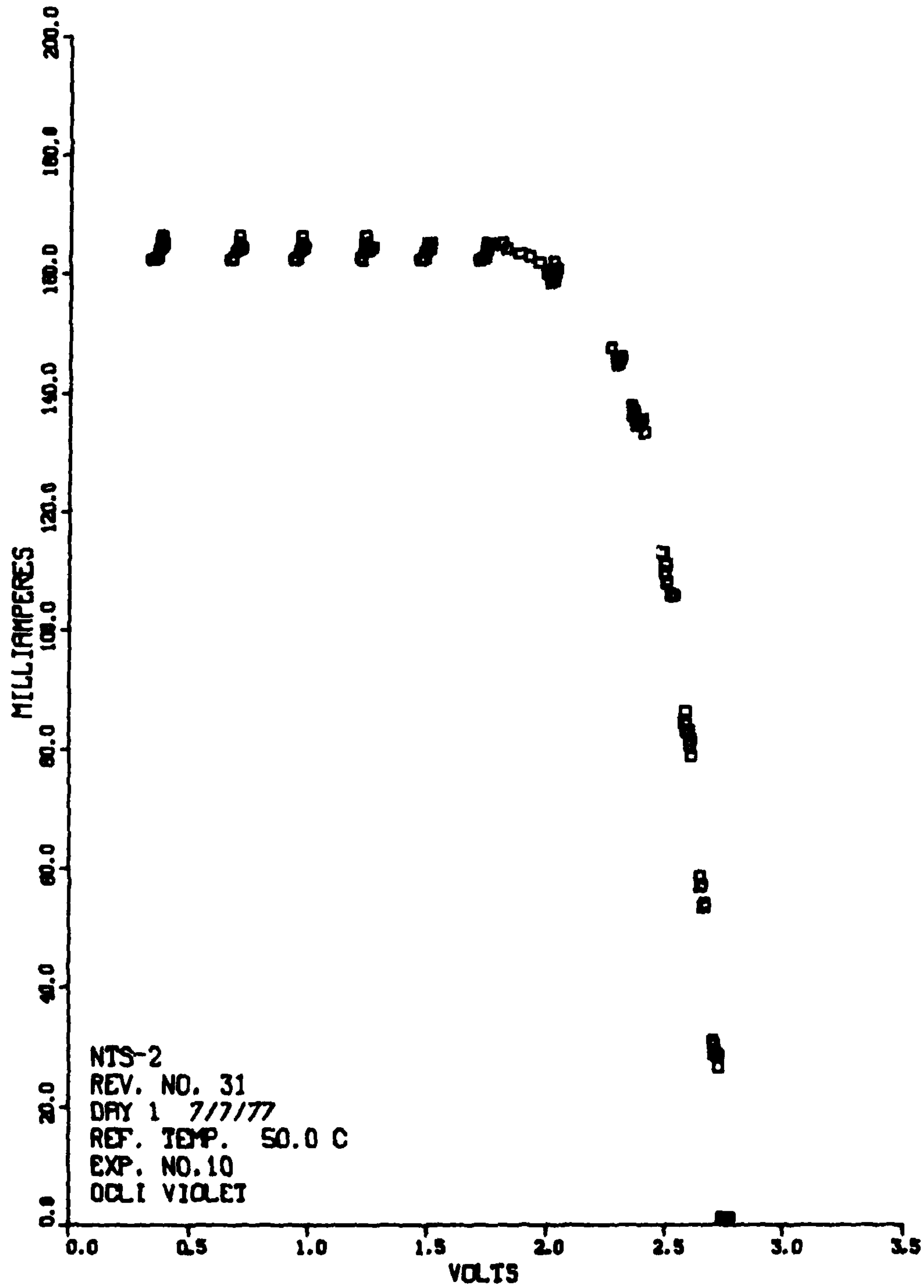

Figure 2 A typical current-voltage data curve as received from the NTS-2 satellite, corrected for solar intensity, sun angle and to a temperature of 50°C.

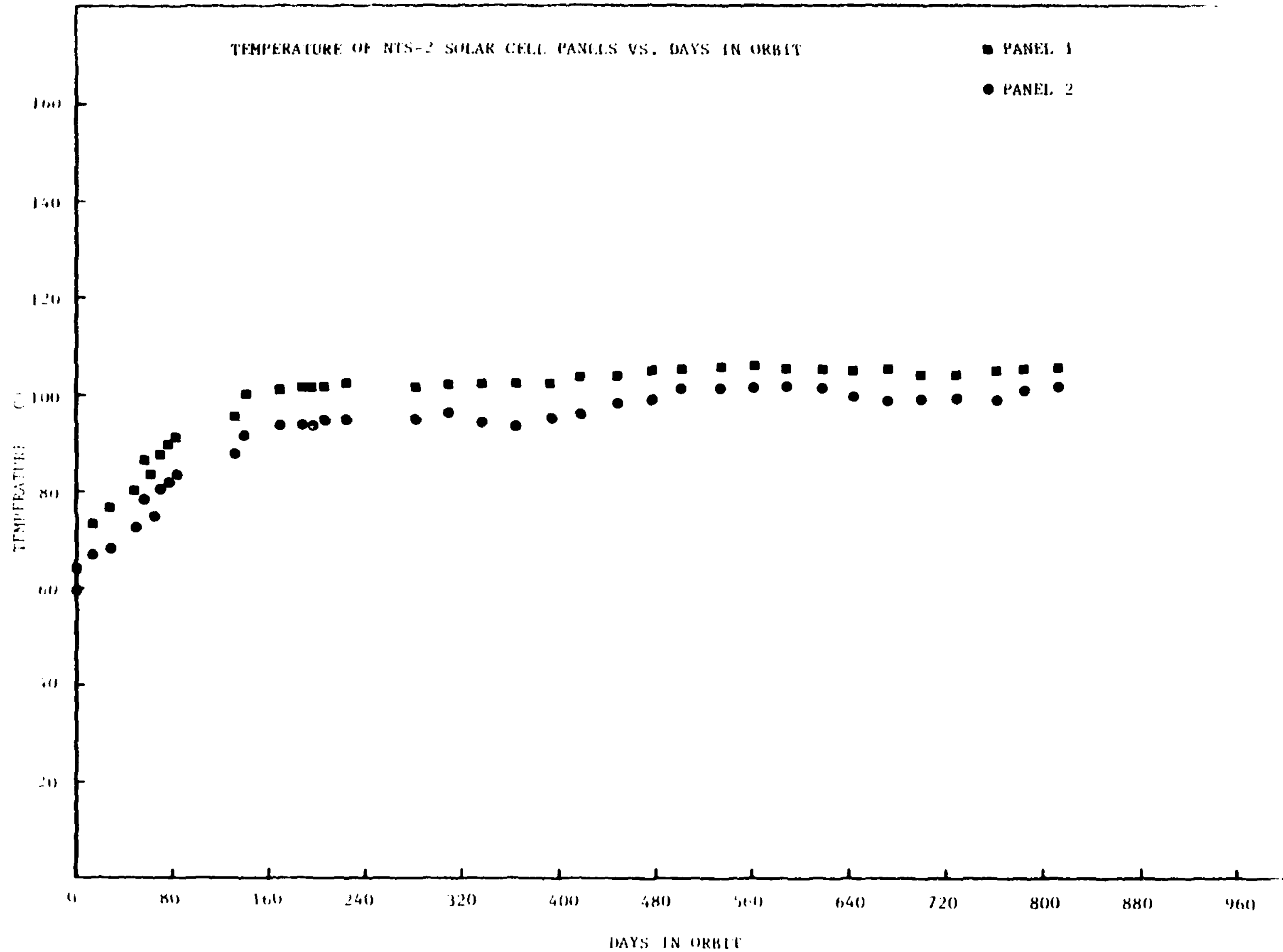

Figure 3 The average temperatures of the solar cell panels over the first 447 days in orbit.

degradation of the white silastic thermal control coating, DC 92007, that covers all panel areas surrounding the solar cell modules. The coated area totals 52 percent of the panels' surface. A closeup view of the panels is shown in Figure 4. It is possible that exposure to ultraviolet and particle radiation has increased the solar thermal absorptivity (α_s) of the thermal control coating from 0.27 to about 0.45, which would account for the higher temperature. Table I gives a brief description of the experiments, showing the type and thickness of the solar cell, the type and thickness of the coverslip, the nature of the coverslip to cell bonding, the interconnect material, and the beginning-of-life (BOL) cell efficiency.

The first short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) data measured in space were in excellent agreement with the ground calibrations which were done at NRL and AFAPL. The data have been corrected for solar intensity (day of the year), for solar aspect angle and to a cell temperature of 50°C. The average spread in I_{sc} between NRL and AFAPL was only 2 mA; the average of these measurements is used as the ground calibration numbers reported here. The average error between I_{sc} on the first day in space and the pre-flight values is 1.41 $\pm$ 0.99 percent. The difference between V_{oc} in space and solar simulator values is 1.24 $\pm$ 1.08 percent. These are much more accurate results than were obtained for the NTS-1 solar cell experiment.[13] The initial NTS-1 experiment I_{sc} data deviated from the ground calibration values by as much as 15 percent for some modules. The average error between maximum power (P_m) measurements on the ground and the first day in orbit was 3.33 $\pm$ 3.17 percent. The greatest difference was for the gallium arsenide cell, where the difference was 12.3 percent. This is not attributed entirely to measurement error, but it is believed there was a possibility for physical change in the cell module in the time between the last ground calibration with a solar simulator and the space measurement (145 days). The GaAs cell module showed a signficant amount of P_m and V_{oc} recovery or "annealing" after 80 days in space (see Figure 5).

Four experiments have either failed completely or sustained unpredictably large degradations. The first of these, the Solarex "Low Cost Space Cell", Experiment 8, experienced an open-circuit of the module on the 69th day, causing the complete loss of subsequent data. Fortunately this failure occurred during a time while data were being recorded, allowing the abrupt manner in which it failed to be observed. The suddenness of the failure is shown in Figure 6. Analysis of the data acquisition system showed that no single point failure of the data system could result in both voltage and current data loss. Therefore it is presumed the module open-circuited.

A second anomaly was the sudden onset of increased degradation rate in the Solarex vertical junction cell, Experiment 7 (Figure 7). At this time there have been five sudden drops in the maximum power output of the vertical junction cells. These sharp decreases have occurred around day 20 in orbit, close to day 180, between day 365 and day 390, and near day 560. The onset of the fifth event occurred about day 729. However, due to subsequent failure the next point on the degradation curve was not received. The failure appears to be permanent as we have obtained no further data from the

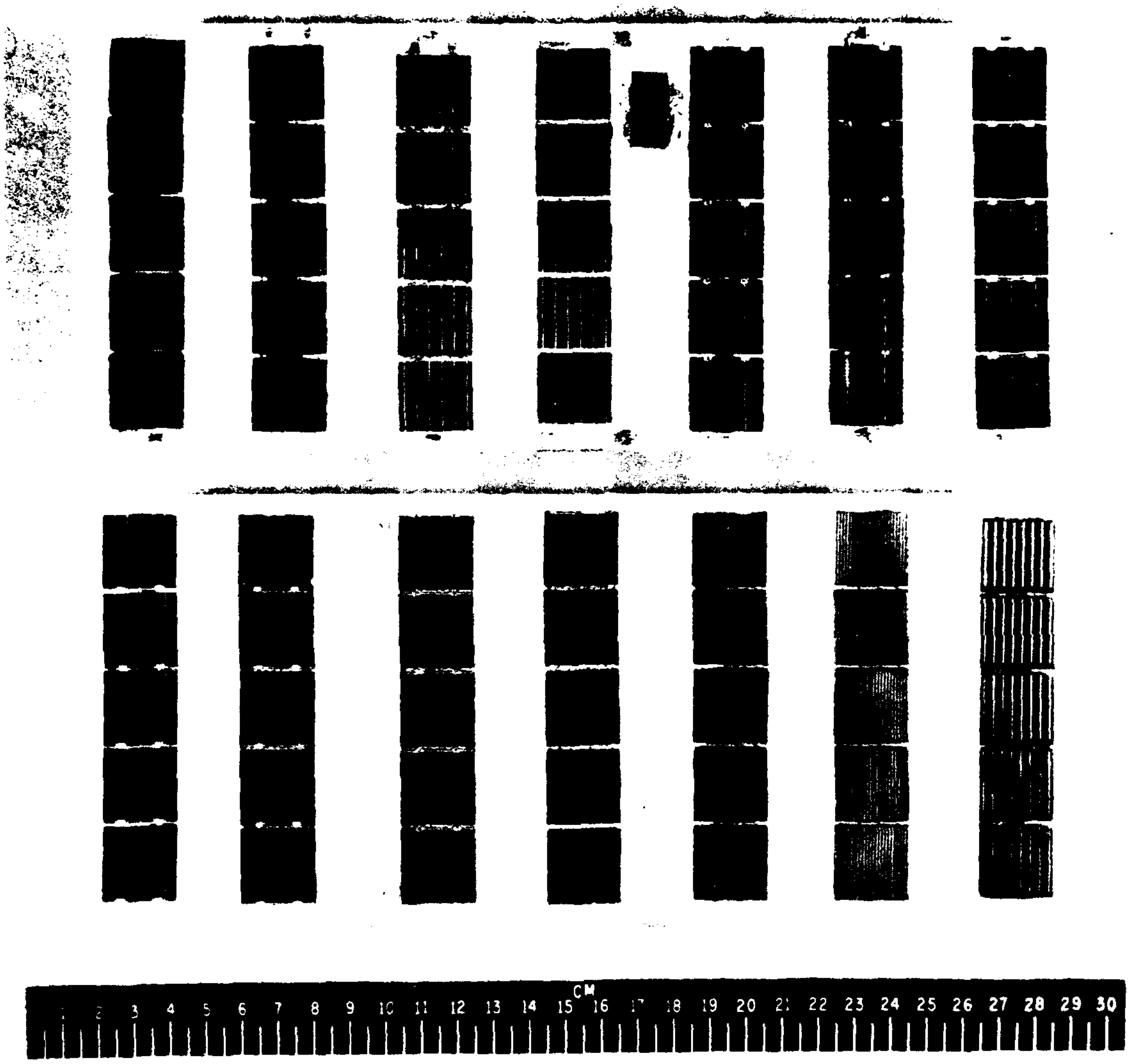

Figure 4 The NTS-2 solar cell experiment modules as mounted on the flight panels

Table I — NTS-2 Solar Cell Experiments

Exp. No.	Cell Type	Thickness (cm)	Coverslip (cm)	Coverslip Bond (cm)	Interconnect	Efficiency 28°C (%)
1	OCLI Conventional, 2 ohm-cm	0.025	Corning 7940, AR and UV, (0.030)	R63-489	Cu/Ag	10.7
2	Spectrolab "Helios" p^+ 15-45 ohm-cm	0.0228	Ceria microsheet w/o AR, (0.025)	DC 93-500	Moly/Ag (.0025)	11.5
3	Spectrolab Hybrid Sculptured 7-14 ohm-cm	0.020	Corning 7940, AR and UV, (0.0152)	DC 93-500	Moly/Ag (.0025)	10.5
4	Spectrolab Hybrid Sculptured 7-14 ohm-cm	0.020	Corning 7940, w/o AR or UV, (0.0152)	FEP Teflon (0.0051)	Moly/Ag (.0025)	11.1
5	Comsat Non-Reflecting, p^+ Textured, 1.8 ohm-cm	0.025	Corning 7940, AR, w/o UV (.030)	R63-489	Ag; thermo-compression bonding	14.5
6	Comsat Non-Reflecting, p^+ Textured, 1.8 ohm-cm	0.025	Corning 7940, AR and UV (.030)	R63-489	Ag; thermo-compression bonding	14.6
7	Solarex Vertical Junction, p^+, 1.5 ohm-cm	0.030	Ceria microsheet w/o AR (.0152)	Sylgard 182	Ag mesh	13.0
8	Solarex Space Cell, p^+ 2 ohm-cm	0.025	Ceria microsheet w/o AR (0.0152)	Sylgard 182	Ag mesh	12.8
9	Spectrolab "Helios" p^+ Sculptured, BSR, 10 ohm-cm	0.030	Corning 7940 (.030) w/o AR or UV	FEP teflon (.003)	Ag mesh (.003)	14.2
10	OCLI Violet, 2 ohm-cm	0.025	Corning 7940 (.030) AR and UV	R63-489	Cu/Ag	13.5
11	Spectrolab P/N Li-doped 15-30 ohm-cm, Al contacts	0.020	Corning 7940, AR and UV, (0.015)	Silicone	Aluminum (.0025) Ultra-sonic welding	10.8
12	Spectrolab Planar Diode in series with Exp. 11	NA	NA	NA	NA	NA
13	OCLI Conventional, 2 ohm-cm	0.025	Corning 7070 (.028)	Electrostatic bonding	Cu/Ag	10.2
14	Spectrolab HESP, no p^+, Sculptured, 2 ohm-cm	0.030	Corning 7940, AR and UV (0.0305)	R63-489	Moly/Ag (.0025)	13.6
15	Hughes Gallium-Aluminum Arsenide	0.0305	Corning 7940, AR and UV, (0.0305)	DC 93-500	Aluminum GPD (.0025), epoxy	13.6

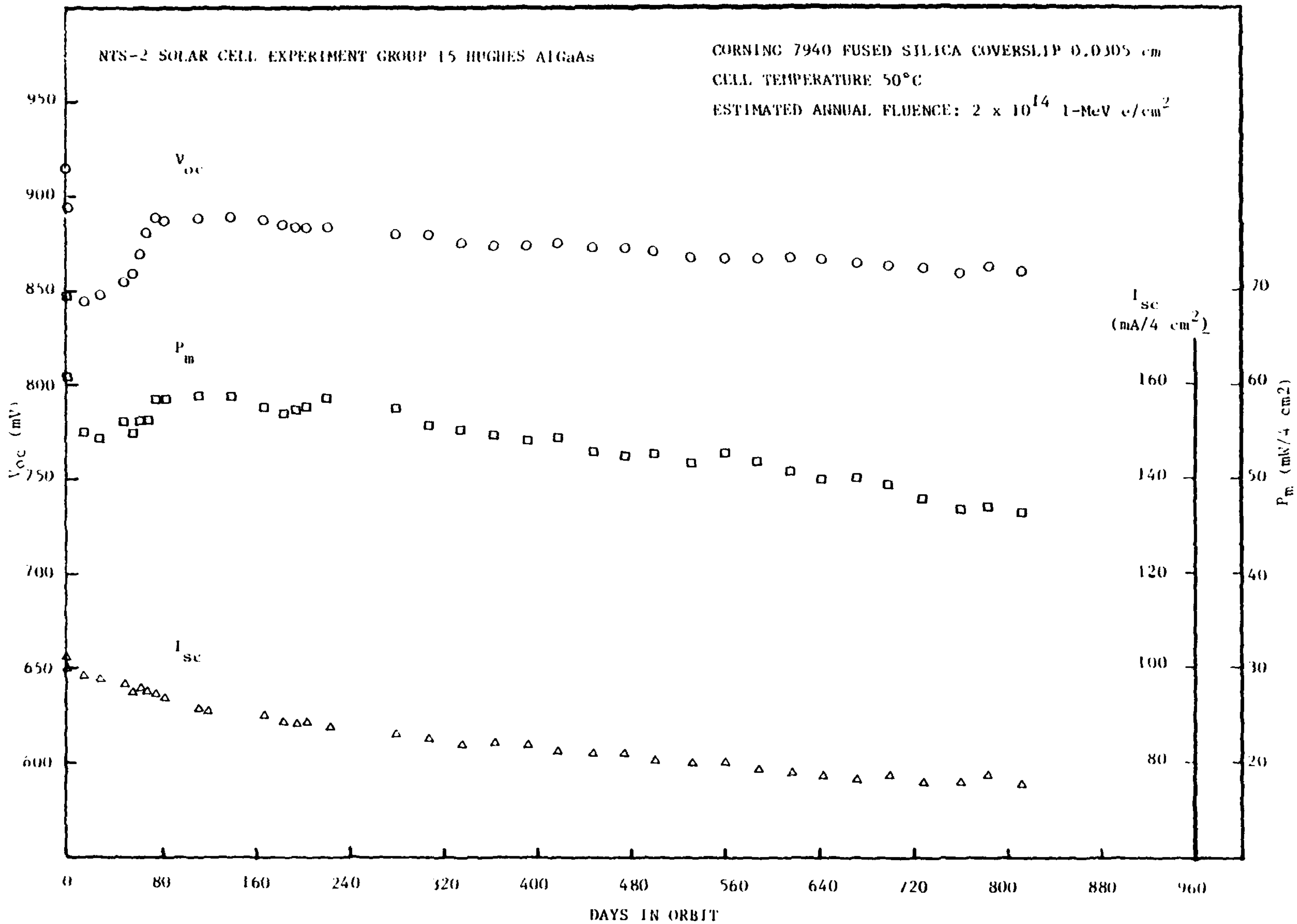

Figure 5 Maximum power, short-circuit current, and open-circuit voltage degradation of the Hughes gallium arsenide cell. P_{max} and I_{sc} are normalized to 4 cm^2. (Experiment 15)

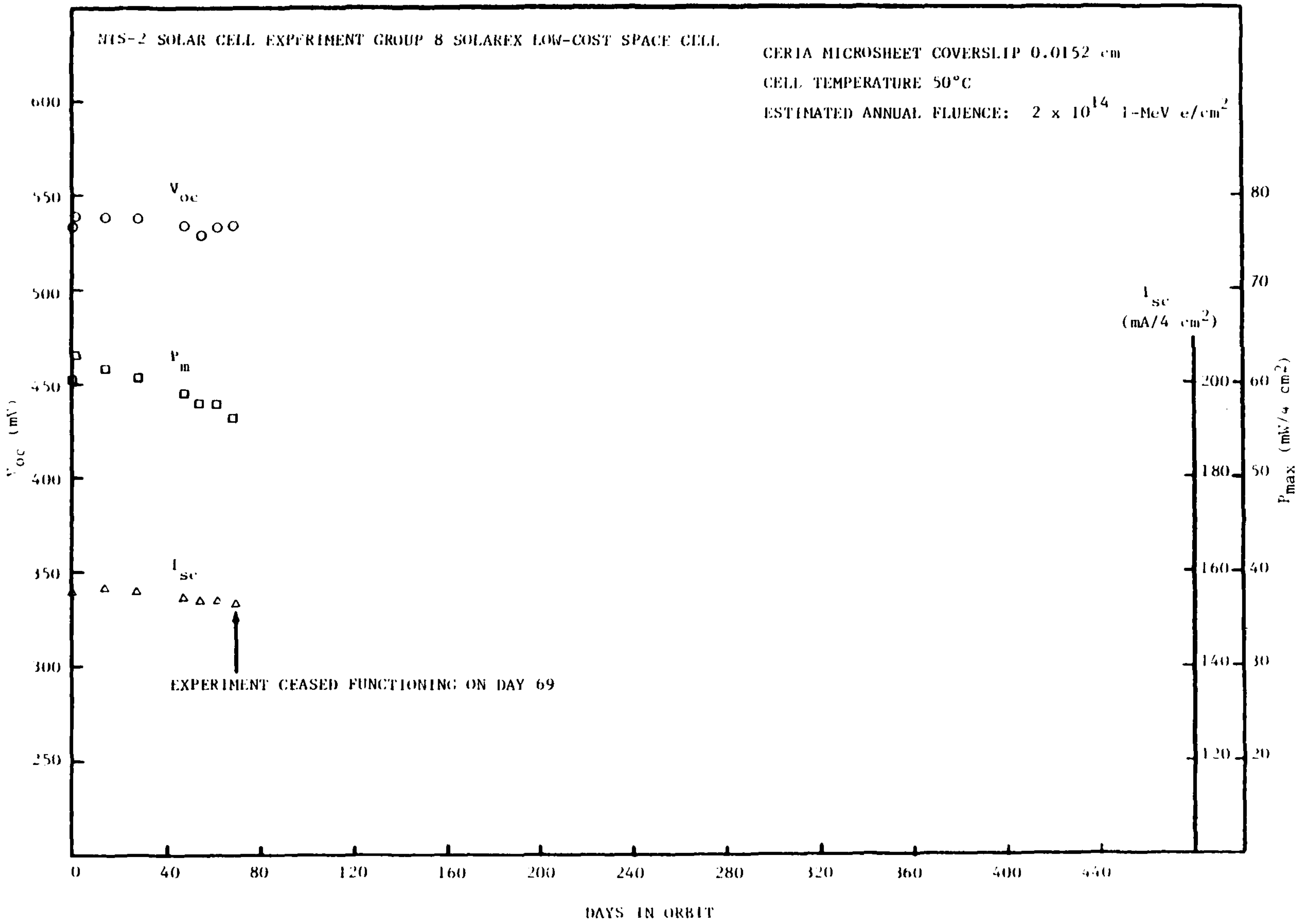

Figure 6 Maximum power, short-circuit current, and open-circuit voltage degradation of the Solarex "low-cost space cell". P_m and I_{sc} are normalized to 4 cm^2. (Experiment 8)

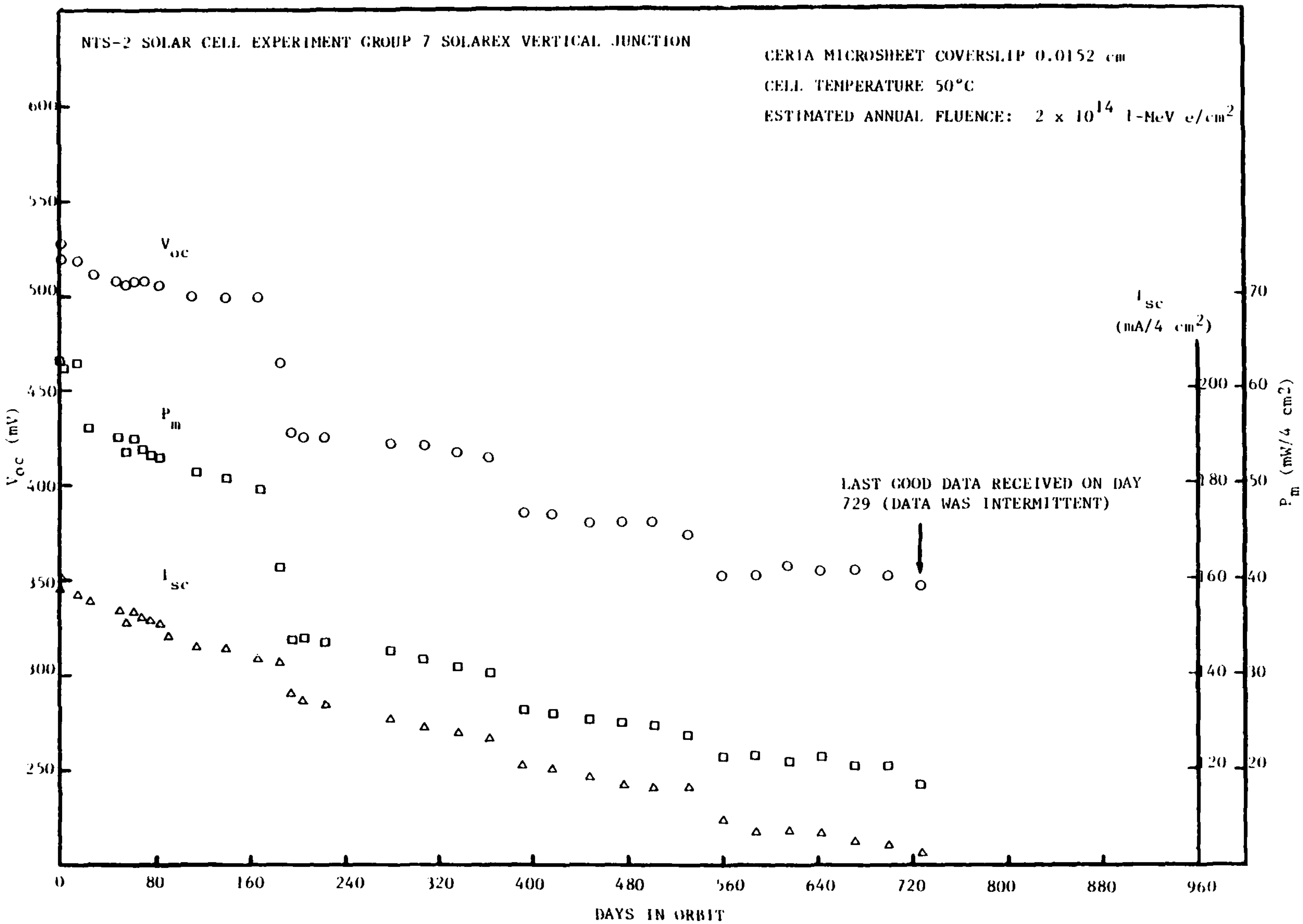

Figure 7 Degradation in maximum power, short-circuit current and open-circuit voltage of the Solarex vertical junction solar cell. P_m and I_{sc} are normalized to 4 cm^2. (Experiment 7)

vertical junction cells. Investigations directed by the Air Force Aero Propulsion Laboratory (AFAPL)[14] suggest that these unusually large losses in maximum power are the result of junction disintegration due to thermal cycling of adhesively bonded-coverslipped cells. The data in Figure 8 seem to support this hypothesis. These abnormal drops in power occur at approximately the same time as the daily maximum duration of the eclipse. As the cells experience increasingly longer periods at temperatures of -40°C, more of the junction is destroyed resulting in power loss. The breakdown of the junction is thought to be related to the type of adhesive used to bond the coverslip. Following each drop in P_m prior to this latest thermal cycle, the power output stabilized quite well until the next maximum duration of the eclipse. The decrease in P_m output of the vertical junction cell by day 729 was 70.7 percent. The data received at that time was intermittent, i.e., an I-V curve was not produced for every scan made during that revolution.

The third unusual occurrence is the large degradation rate for Experiment 5, the COMSAT CNR cell covered with a 12 mil (0.305 cm) fused silica coverslip which has no ultraviolet cut-off filter. The COMSAT textured cell was flown both with and without an ultraviolet rejection filter in order to evaluate the effect of the filter. The P_m of this cell has decreased 52.1% down to 35.8 mW after 811 days, while Experiment 6, an identical module except for the addition of the ultraviolet cut-off filter on the coverslip, has a P_m of 52.0 mW, a drop of only 27.8 percent. Although the two arrays started with approximately the same beginning-of-life short-circuit current, the I_{sc} of the cells with the uv filter (Experiment 6) has degraded only 23.6 percent. However, the I_{sc} of Experiment 5 without the uv filter is down by 45.8 percent. Figure 9 shows the short-circuit current degradation of the COMSAT textured cell in both configurations. This amount is much greater than was expected solely from the absence of the uv filter. Previous experiments indicated that degradation from ultraviolet degradation of the solar cell assembly is about 2 to 4 percent. The damage is thought to occur and stabilize during the first few weeks due to darkening of the adhesive, which in this case, is R63-489. Laboratory measurements at COMSAT Laboratories did not show a substantial difference with or without a filter.[15] If the degradation seen in the I_{sc} of these cells were caused by particle radiation in the cell, the V_{oc} would be severely degraded. Figure 10 shows that the V_{oc} of the cells with and without the uv filter is essentially the same. Neither the fill factor of Experiment #5 nor the knee of its I-V curve, which would be noticeably "softened", show any signs of radiation damage. At this time, the large degradation of the non-filtered cell remains unexplained. There may be an unidentified damage mechanism involved. The flight data for Experiments 5 and 6 are shown in Figure 11 and Figure 12, respectively.

The Spectrolab textured Helios reflector cells comprising Experiment 9 have ceased to transmit data. The development of trouble appears to have been sudden. The last data were received for this experiment on day 721. By the time the next data were received on day 783, there was no output from Experiment 9. Prior to day 783, there had been no indication of any malfunction. The data from Experiment 9 are shown in Figure 13. The remainder of the modules have operated as expected, although degrading more

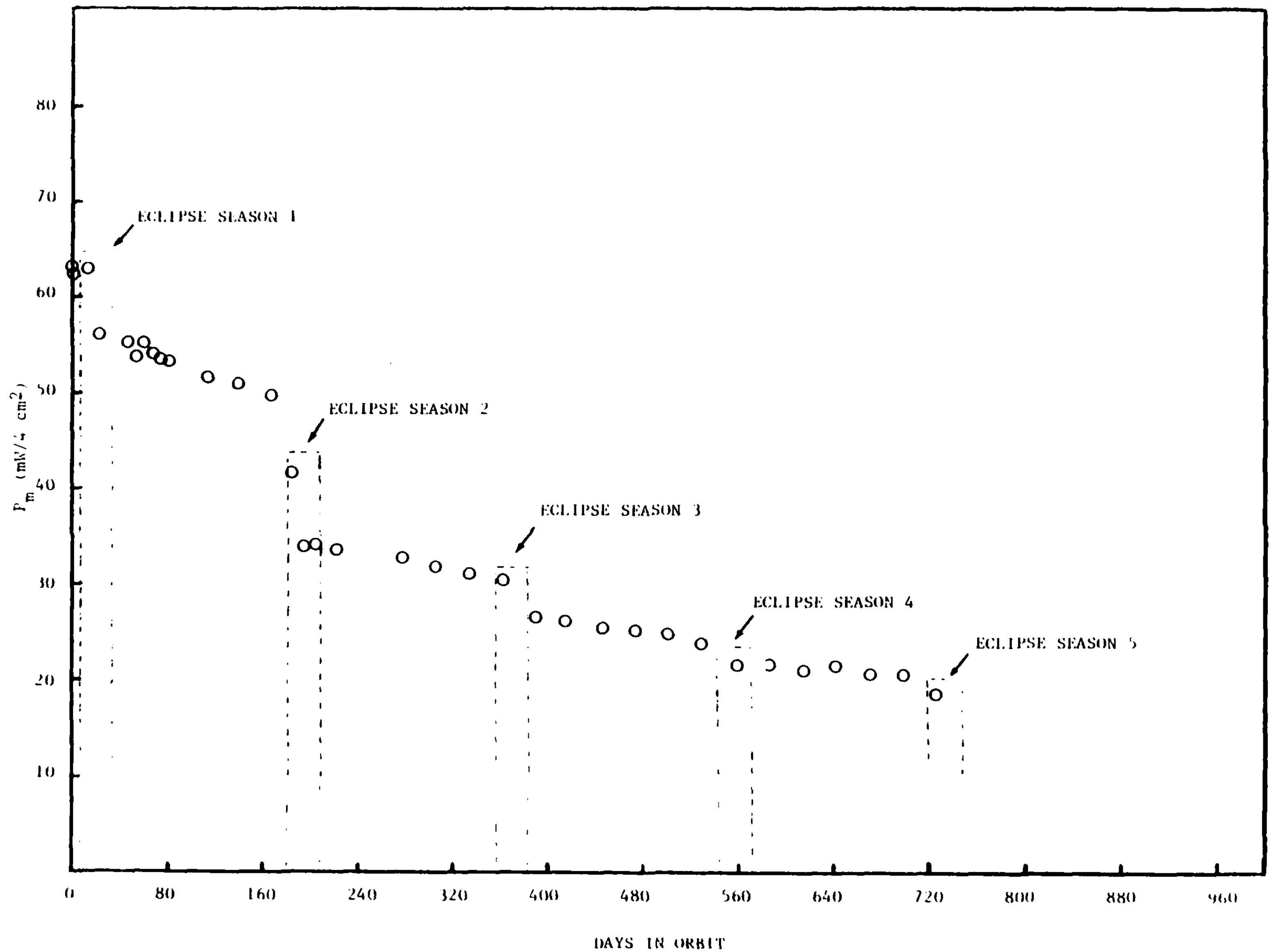

Figure 8 Maximum power degradation of the Solarex vertical junction cell and the duration of the eclipse versus days in orbit. P_m is normalized to 4 cm^2.

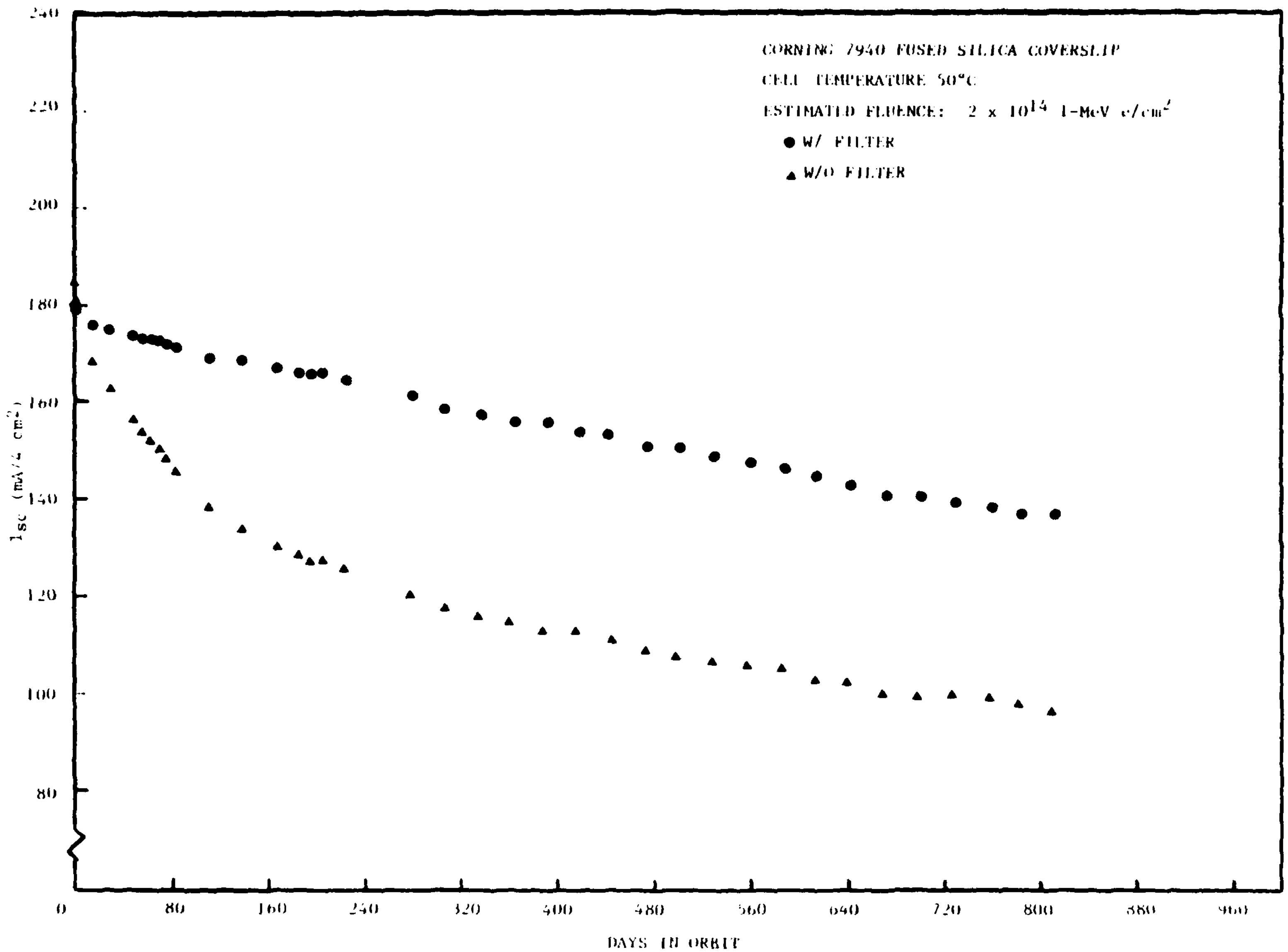

Figure 9 Short-circuit current degradation of the Comsat textured cell both with and without an ultraviolet rejection filter. Data are normalized to 4 cm^2.

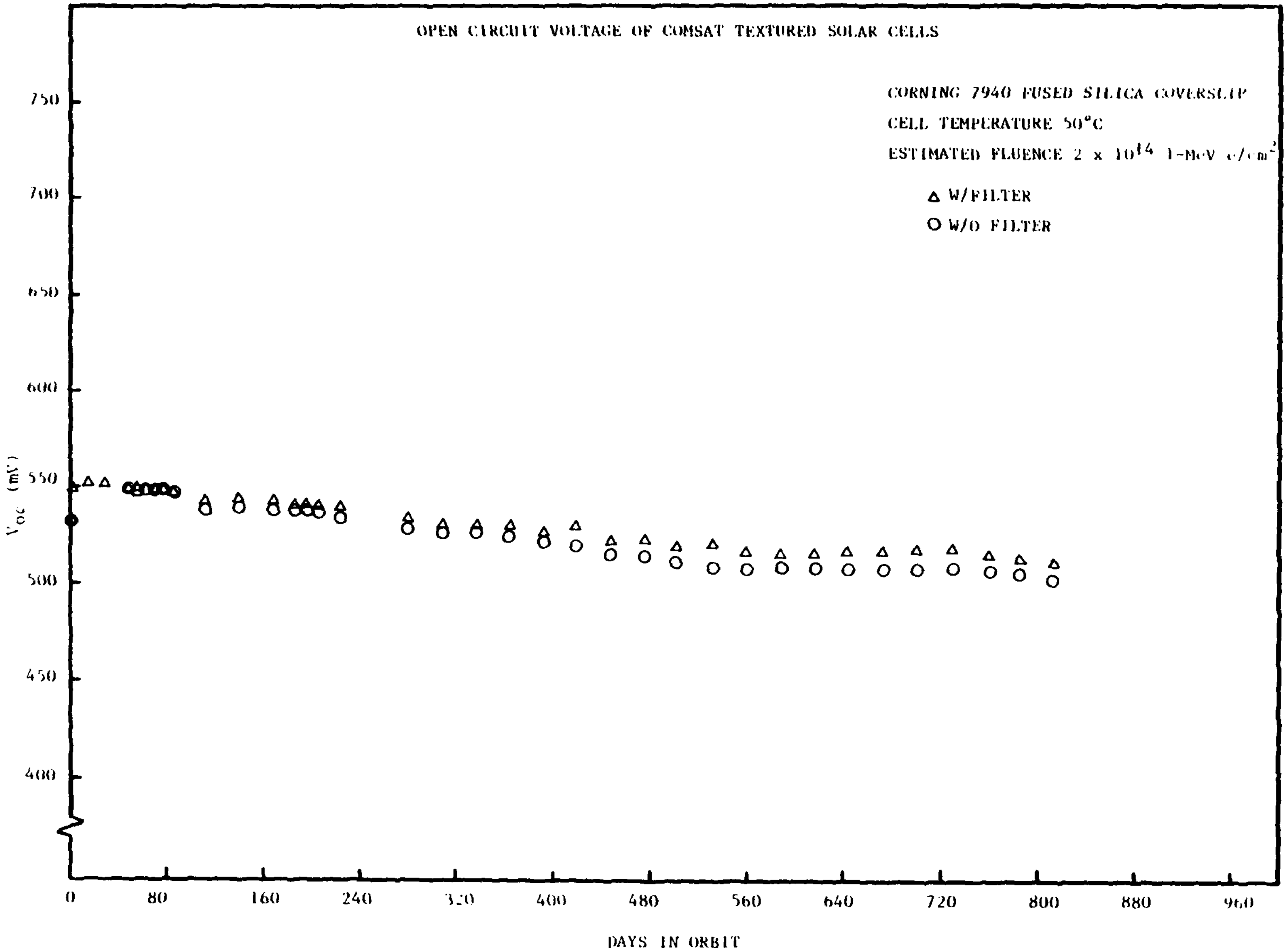

Figure 10 Open-circuit voltage degradation of the Comsat textured cell both with and without an ultraviolet rejection filter.

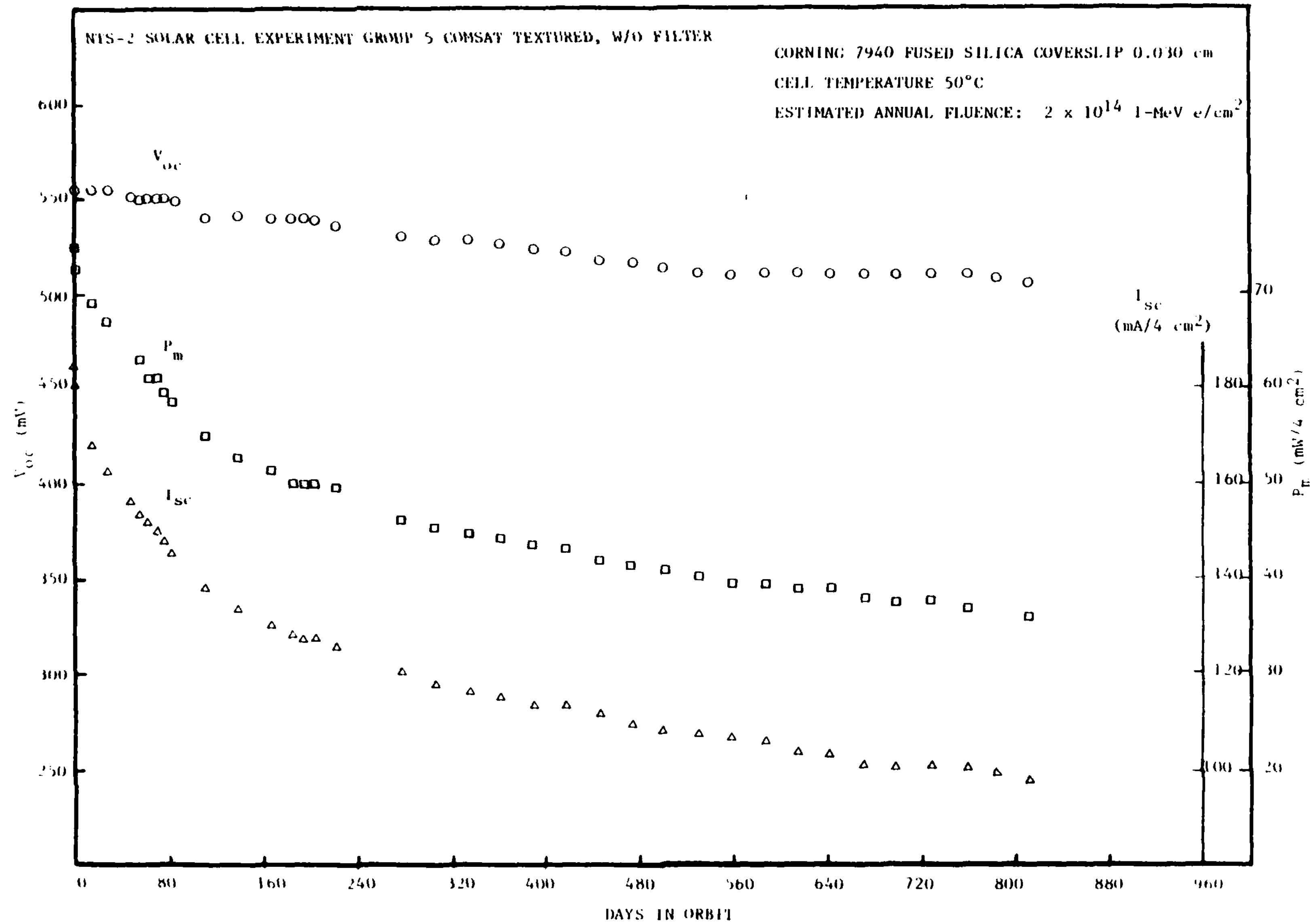

Figure 11 Degradation of maximum power, short-circuit current and open-circuit voltage of the Comsat CNR cell without the uv filter. (Experiment 5)

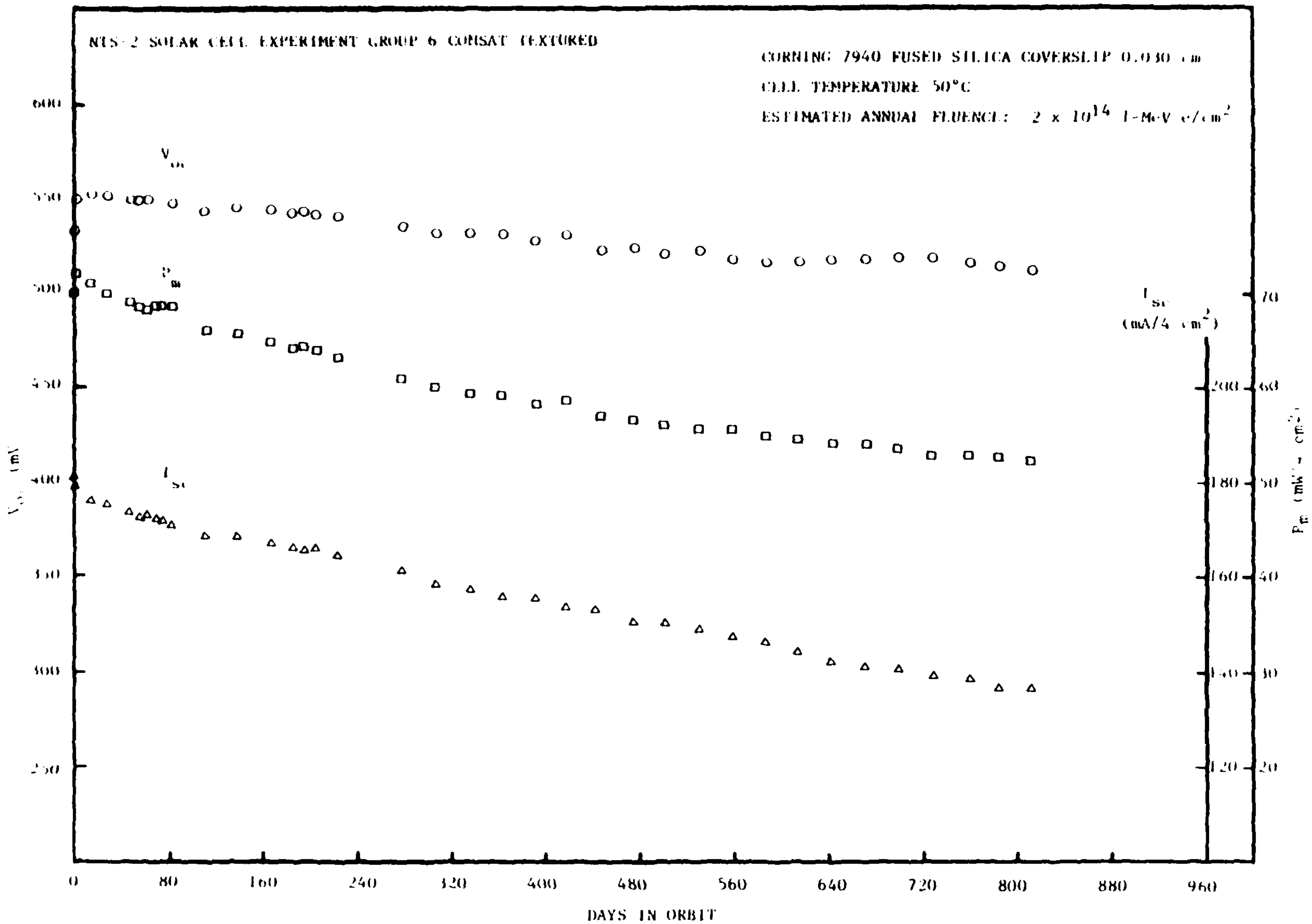

Figure 12 Degradation of maximum power, short-circuit current and open-circuit voltage of the Comsat CNR cell with an ultraviolet rejection filter. (Experiment 6)

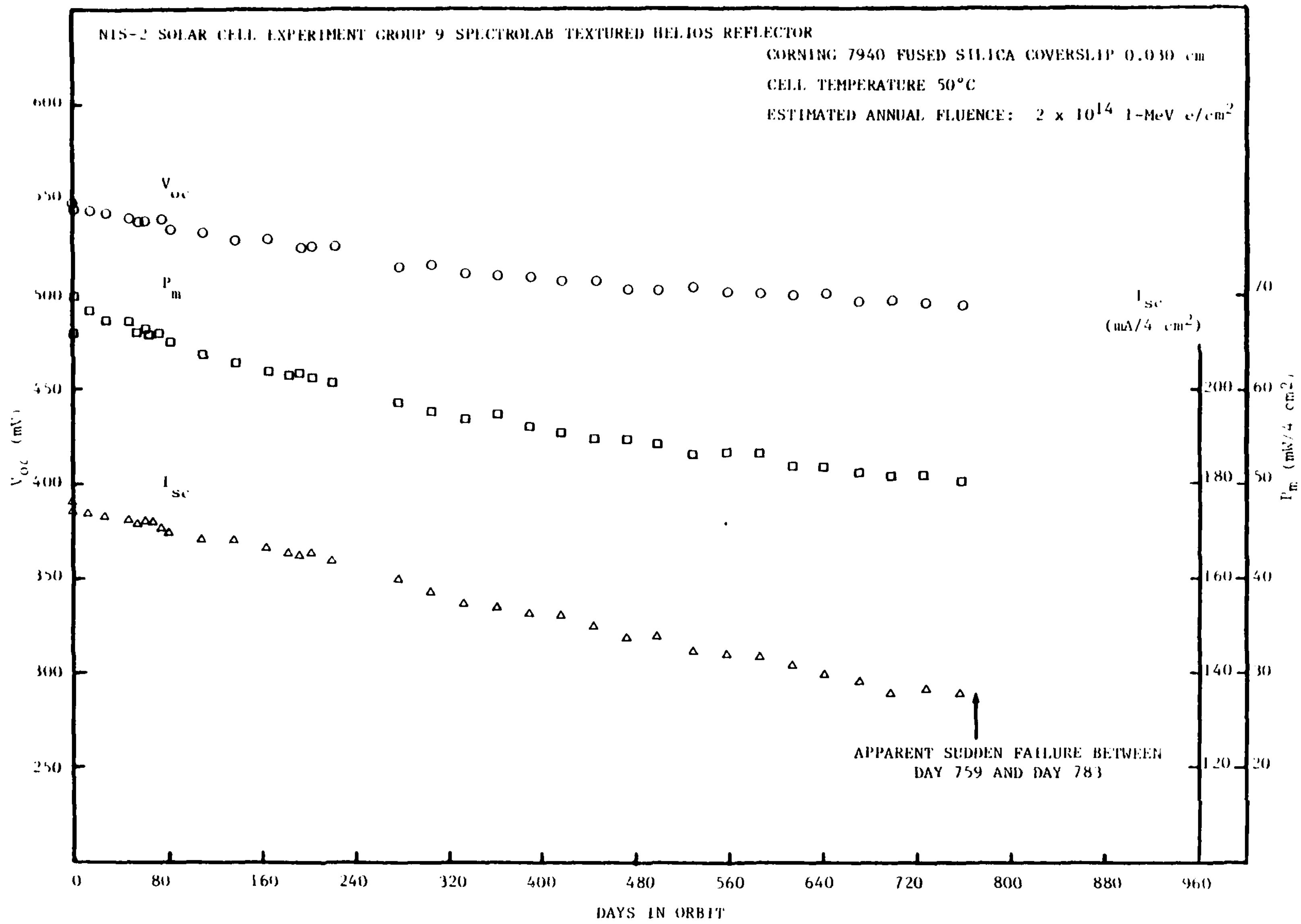

Figure 13 Degradation of P_m, V_{OC} and I_{SC} of the Spectrolab Helios reflector cells. P_m and I_{SC} are normalized to 4 cm^2. (Experiment 9)

rapidly than predicted from the published reports.[16,17] Table II lists the P_m of the experiments at BOL and after 811 days in orbit.

By day 200, the solar cell experiments had been experiencing sufficient radiation damage to allow predictions of future damage rates to be made. The fluence of equivalent 1-MeV electrons/cm^2 experienced by four (4) selected groups of solar cells (Experiment 1, the OCLI conventional cell; Experiment 2, the Spectrolab Helios cell; Experiment 3, the Spectrolab textured hybrid cell and Experiment 10, the OCLI violet cell) by day 200 is tabulated in Table III. These data were used to predict the estimated annual fluence and the fluence expected over 3 years. The corrected space data for these experiments through day 811 are shown in Figures 14-17. The OCLI 2 ohm-cm cell is used as a reference because the effects of varied amounts of fluence on these cells have been studied extensively. The predicted degradation rate of P_m calculated from these experiments for the first three years in orbit is plotted in Figure 18 along with the experimental data from the Helios cells. The flight data indicate the presence of a slightly harder radiation environment than was predicted. The relative degradations of the cells mentioned above, as calculated for day 200, and predicted for 1 year and 3 years, are shown in Table IV. On day 811 the P_m of each of the experiments was approximately 2 percent lower than predicted. The degradation curves for these three modules, Experiments 1, 2, and 10, in Figure 19, were compared with laboratory results of 1-MeV electron irradiation tests of similar cells. From these data we obtained values for DENI space fluence of 1.6-2.7 x 10^{14} 1-MeV electron/cm^2 year.

Among the experiments of primary interest is the Spectrolab "Helios" back field cell, Experiment #2. This cell was space qualified as one of the experiments aboard the NTS-1 satellite. The "Helios" cell is presently in use as the main power source on NTS-2 and is in use in other satellite programs. As of day 811, the maximum power output of the Spectrolab Helios cell (NTS-2) has decreased by 28.9 percent. The maximum power plotted versus days in orbit for this experiment is shown in Figure 15. Interestingly, although the Spectrolab Helios cell degraded less than a conventional cell in I_{sc} and P_m, its V_{oc} output continued to degrade at a faster rate.

The performance of the Hughes gallium arsenide cell has been followed with great interest. The gallium arsenide cell is a high-efficiency solar cell that is expected to be radiation hardened and therefore be especially suited to space applications. The historical problems of high surface recombination and low lifetime in the diffused region are largely overcome by the addition of a GaAlAs window. The array of Hughes Research Laboratory's gallium arsenide (GaAlAs/GaAs) solar cells comprises Experiment #15 on NTS-2. The degradation in I_{sc}, V_{oc} and P_m versus days in orbit are shown in Figure 5. The gallium arsenide module at first exhibited the smallest power loss; while no longer the least, after 811 days its power has decreased by 24.8 percent.

TABLE II
NTS-2 MAXIMUM POWER OUTPUT FOR SOLAR CELL EXPERIMENTS

EXPERIMENT NO.	CELL TYPE	MAXIMUM POWER OUTPUT (mW/4 cm^2)* SOLAR SIMULATOR	DAY 1 IN ORBIT	DAY 811 IN ORBIT	% LOSS DAY 1 TO DAY 811
1	OCLI Conv. 2 ohm-cm	53.1	56.3	38.5	31.6
2	Spectrolab Helios (NTS-2)	57.9	60.6	43.1	28.9
3	Spectrolab Text. Hybr., F.S.	52.4	53.5	40.0	25.2
4	Spectrolab Text. Hybr., FEP, F.S. w/o filter	54.6	55.4	44.0	20.6
5	Comsat Text. F.S., w/o filter	72.8	74.7	35.8	52.1
6	Comsat Text. F.S.	70.1	72.0	52.0	27.8
7	Solarex Vert. Junc.	63.1	62.2	-	100
8	Solarex Space Cell	60.6	63.1	-	100
9	Spectrolab Text. Helios Reflector	66.0	70.0	-	100
10	OCLI Violet, F.S.	67.5	66.6	49.5	25.7
11	Spectrolab HASP w/o diode	53.2	55.8	41.3	26.0
12	Spectrolab HASP w/diode	42.0	42.1	30.0	28.7
13	OCLI Conv., ESB	47.0	46.8	36.0	23.1
14	Spectrolab HESP	63.3	63.8	45.8	28.2
15	HRL AlGaAs	70.0	61.4	46.2	24.8

*These data have been corrected to 50°C at one-sun and air mass zero (AMO).

Table III — NTS-2 Equivalent Fluence (1 - MeV e/cm^2) Predictions*

OCLI Conventional 2 Ω-cm, 10 mil cell, 12 mil FS Coverslip

BOL		Fluence at 200 days	Fluence at 1 yr	Fluence at 3 yr
I_{sc}	136.0 mA	1.5×10^{14}	2.7×10^{14}	8.2×10^{14}
V_{oc}	548 mV	3×10^{13}	5.5×10^{13}	1.6×10^{14}
P_m	56.5 mW/4 cm^2	1.3×10^{14}	2.4×10^{14}	7.1×10^{14}
Spectrolab Helios, 10 Ω-cm, 9 mil cell, 10 mil Ceria Coverslip				
BOL		Fluence at 200 days	Fluence at 1 yr	Fluence at 3 yr
I_{sc}	154 mA	1.3×10^{14}	2.4×10^{14}	7.1×10^{14}
V_{oc}	545 mV	1×10^{13}	1.8×10^{13}	5.5×10^{13}
P_m	60.5 mW/4 cm^2	9×10^{13}	1.6×10^{14}	4.9×10^{14}
Spectrolab Textured Hybrid, 8 mil cell, 6 mil FS Coverslip				
BOL		Fluence at 200 days	Fluence at 1 yr	Fluence at 3 yr
I_{sc}	156 mA	5.0×10^{14}	9.1×10^{14}	2.7×10^{15}
V_{oc}	522 mV	5.0×10^{14}	9.1×10^{14}	2.7×10^{15}
P_m	53.8 mW/4 cm^2	3.3×10^{14}	6.0×10^{14}	1.8×10^{15}
OCLI Violet				
BOL		Fluence at 200 days	Fluence at 1 yr	Fluence at 3 yr
I_{sc}	166 mA	1×10^{13}	1.8×10^{14}	5.5×10^{14}
V_{oc}	552 mV	2×10^{13}	3.7×10^{13}	1.1×10^{14}
P_m	67.5 mW/4 cm^2	7.5×10^{13}	1.4×10^{14}	4.1×10^{14}

*Cell data at 50°C

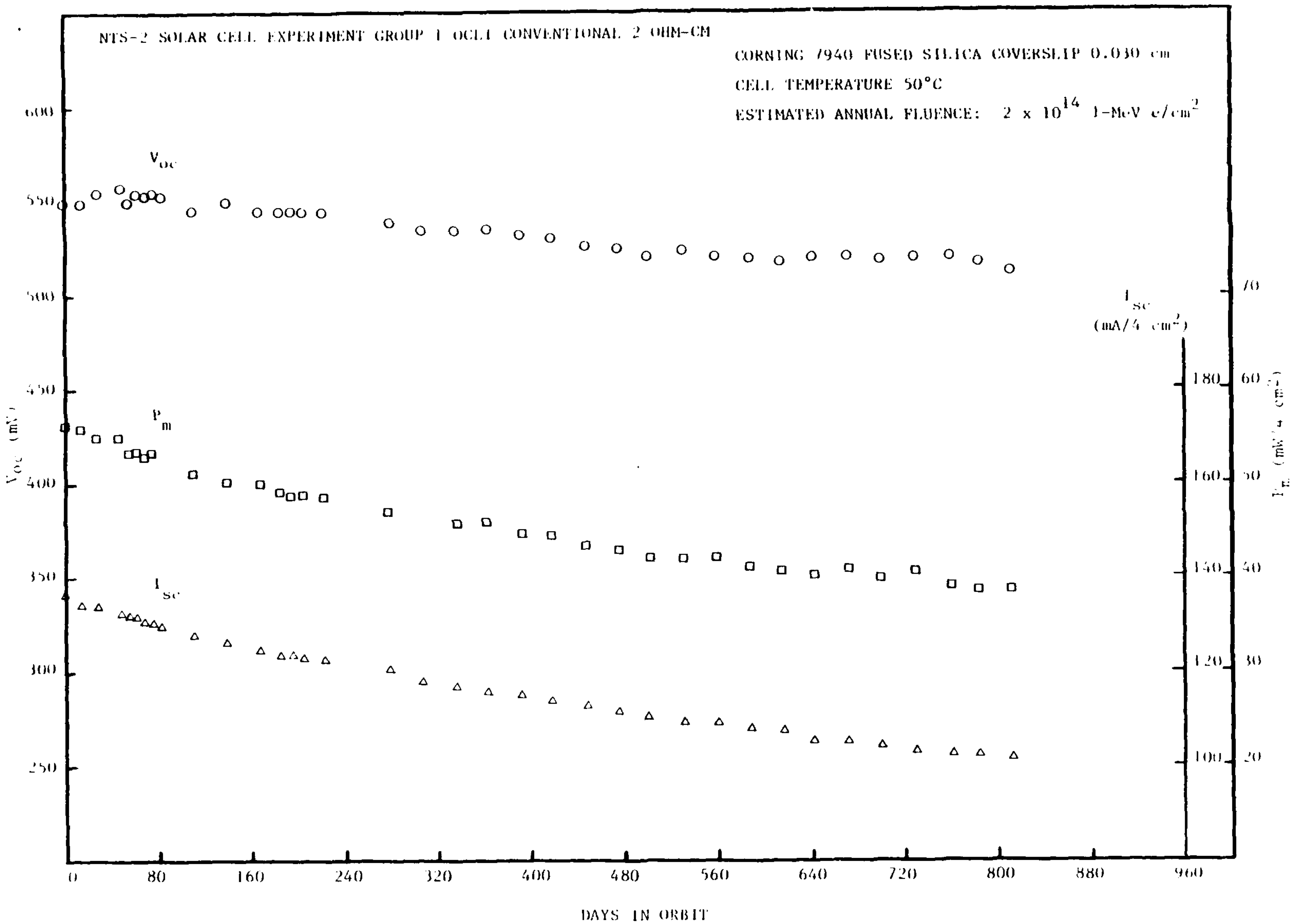

Figure 14 Degradation of maximum power, short-circuit current and open-circuit voltage of the OCLI conventional solar cell. P_m and I_{sc} are normalized to 4 cm^2. (Experiment 1)

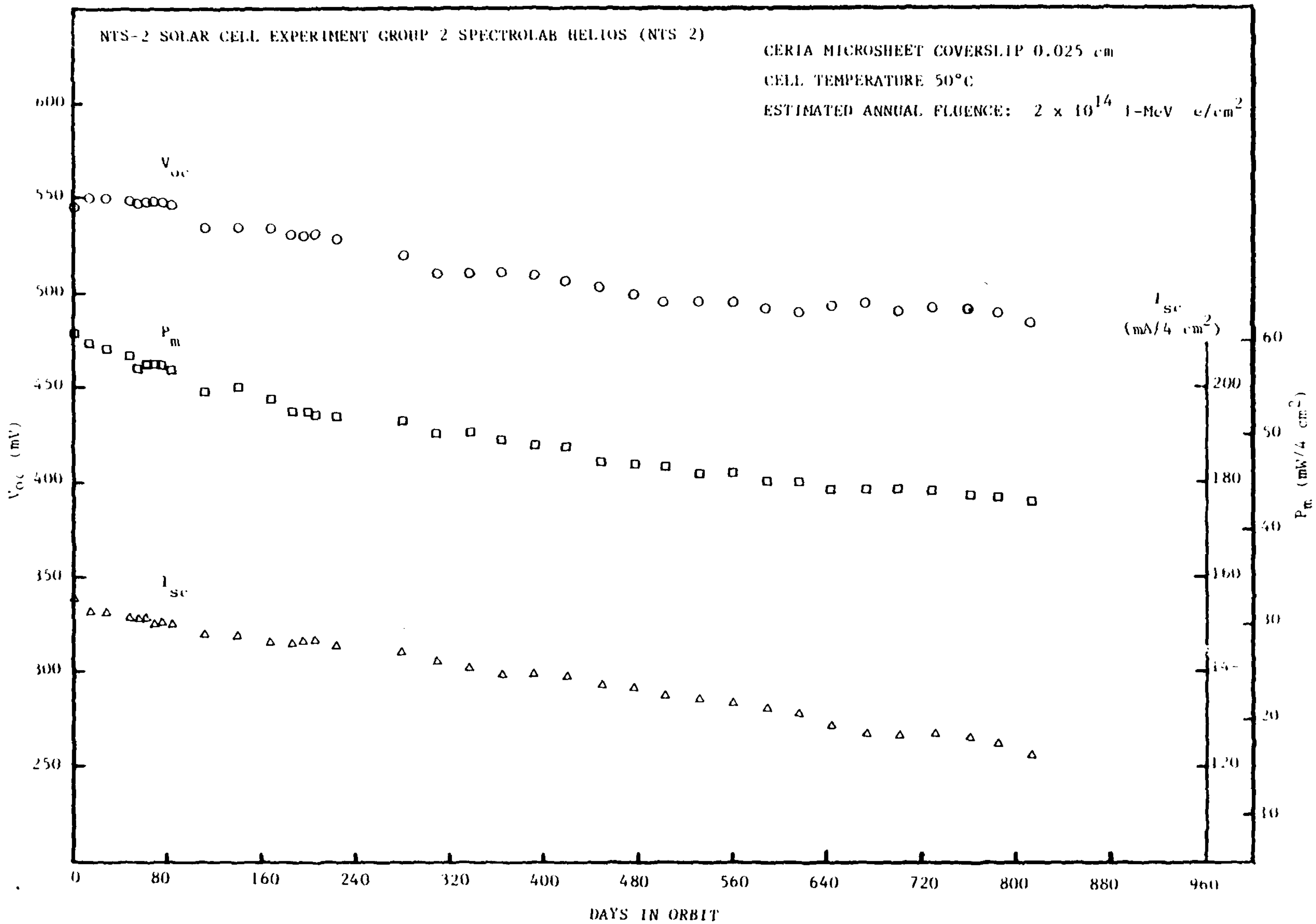

Figure 15 Degradation of P_m, I_{SC} and V_{OC} of the Spectrolab Helios cell. P_m and I_{SC} are normalized to 4 cm^2. (Experiment 2)

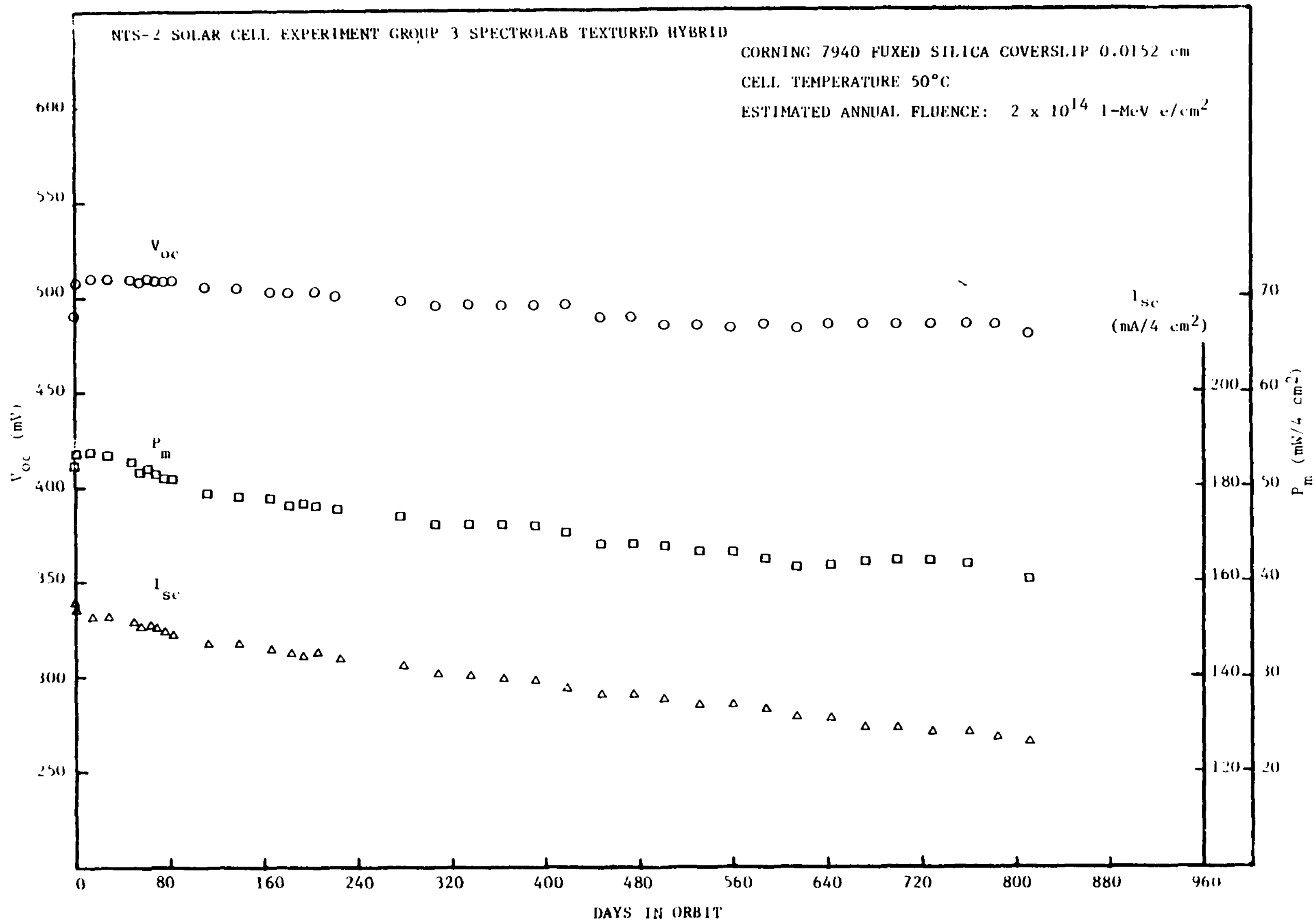

Figure 16 Degradation of P_m, I_{SC} and V_{OC} of the Spectrolab textured hybrid cell. P_m and I_{SC} are normalized to 4 cm^2. (Experiment 3)

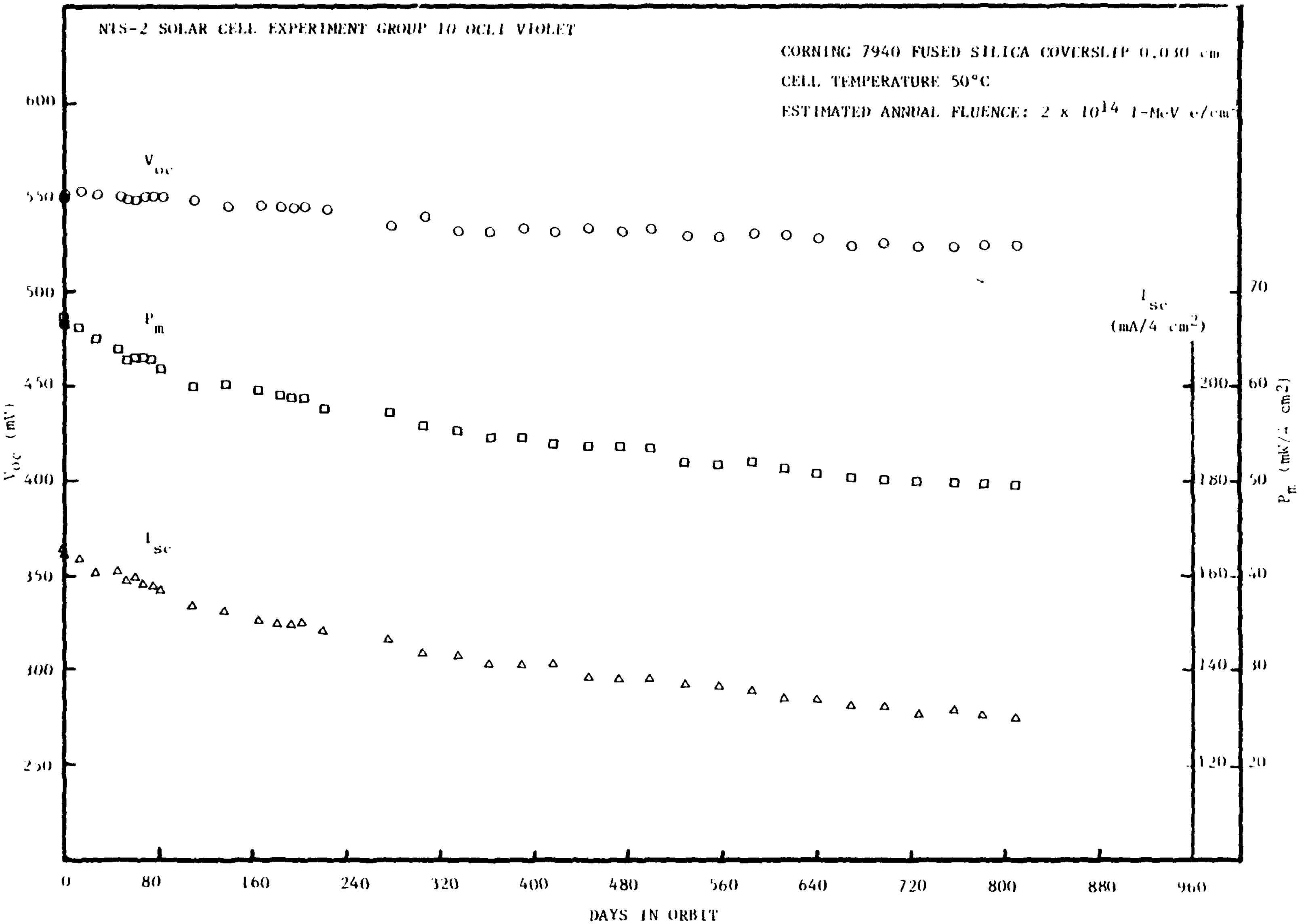

Figure 17 Degradation of P_m, I_{sc} and V_{oc} of the OCLI violet. P_m and I_{sc} are normalized to 4 cm^2. (Experiment 10)

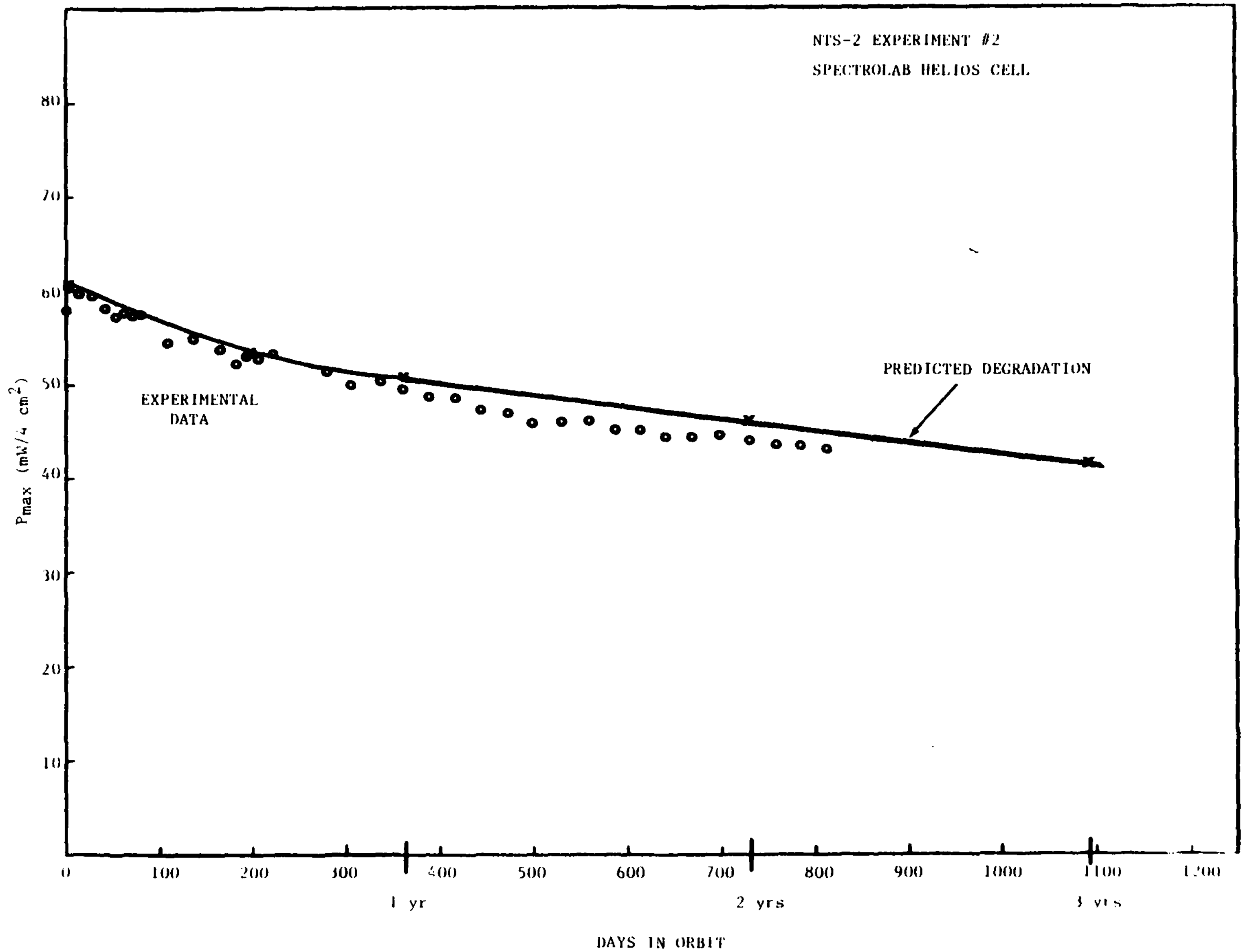

Figure 18 Predicted degradation rate for the Spectrolab Helios cell over a three-year period.

Table IV — Percent of I_{sc}, V_{oc} and P_{max} Remaining after 200 Days in Orbit and Predictions for Percent Remaining at 1 yr and 3 yrs*

OCLI Conventional, 2 Ω-cm, 10 mil cell, 12 mil FS Coverslip

BOL		Relative Degradation at 200 days	Relative Degradation at 1 yr	Relative Degradation at 3 yrs
I_{sc}	136.0 mA	.91	.87	.81
V_{oc}	548 mV	.98	.97	.94
P_m	56.5 mW/4 cm^2	.87	.82	.75
Spectrolab Helios, 10 Ω-cm, 9 mil cell, 10 mil Ceria Coverslip				
BOL		Relative Degradation at 200 days	Relative Degradation at 1 yr	Relative Degradation at 3 yrs
I_{sc}	154 mA	.95	.91	.87
V_{oc}	545 mV	.98	.96	.93
P_m	60.5 mW/4 cm^2	.88	.84	.76
Spectrolab Textured Hybrid, 8 mil cell, 6 mil FS Coverslip				
BOL		Relative Degradation at 200 days	Relative Degradation at 1 yr	Relative Degradation at 3 yrs
I_{sc}	156 mA	.93	.90	.82
V_{oc}	522 mV	.96	.94	.90
P_m	53.8 mW/4 cm^2	.90	.87	.74
OCLI Violet, 10 mil cell, 12 mil FS Coverslip				
BOL		Relative Degradation at 200 days	Relative Degradation at 1 yr	Relative Degradation at 3 yrs
I_{sc}	166 mA	.90	.84	.80
V_{oc}	552 mV	.98	.97	.95
P_m	67.5 mW/4 cm^2	.87	.83	.75

*Cell data at 50°C

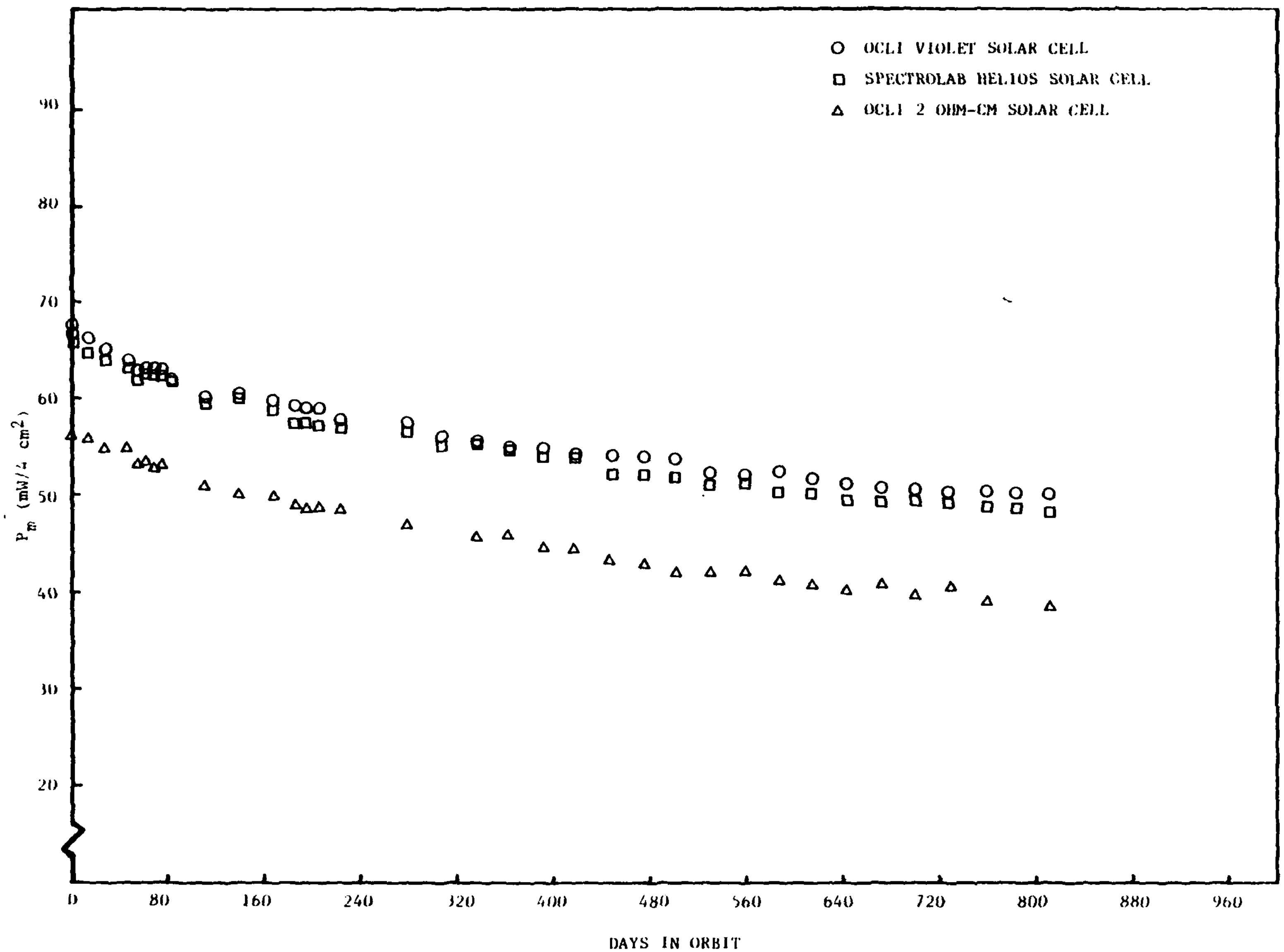

Figure 19   Comparison of power degradation in the OCLI violet, Spectrolab Helios and the OCLI conventional solar cells.

Experiments 3 and 4 were designed to distinguish between cell degradation effects due to adhesive bonding as a function of FEP Teflon bonding. There is a decided improvement for the Teflon bonded coverslip (20.6 percent degradation) using "as sawn fused silica" instead of the traditional polished and uv filtered Corning 7940 fused silica (25.2 percent degradation in P_m). These data are presented in Figures 16 and 20.

Another coverslip evaluation is made in Experiments 1 and 13 which utilize OCLI conventional cells. Experiment 1 has an adhesively bonded Corning 7940 fused silica coverslip and Experiment 13 has a Corning 7070 glass coverslip which was electrostatically bonded (ESB). There is a slight loss in beginning of life P_m with the electrostatic bonding technique. The percentage power loss after 811 days in orbit is much less for the ESB cell at 23.1 percent compared to the 31.6 percent P_m loss in the adhesively bonded cell. These results are shown in Figures 14 and 21.

Experiments 11 and 12 were designed to evaluate the behavior of a diode in series with solar cells in the space radiation environment. The data from Experiment 11 and Experiment 12 are shown in Figures 22 and 23, respectively. As shown in Figure 24, the voltage drop across the diode has not changed significantly over the 811 days in space.

The Spectrolab HESP cells, Experiment 14, have degraded in P_m 28.2 percent, as shown in Figure 25.

The absolute values and percent changes of short-circuit current and open-circuit voltage are listed in Tables V and VI. The percent changes in I_{sc}, V_{oc} and P_m are summarized in Table VII.

Conclusions

The overall performance of the flight experiment and the quality of the data have been excellent. Several important conclusions which have been reached concerning the new cell technologies are listed below.

1. The Spectrolab Helios p^+ (K6) cell with an adhesively-bonded 0.0254 cm ceria microsheet coverslip is an excellent solar cell for the GPS natural environment. The Spectrolab textured hybrid cell with an FEP bonded 0.0152 cm "as-cut" quartz coverslip seems to be equally satisfactory for this orbit.

2. There are two other types of silicon cells which can be classed as production cells whose P_m exceeded the Helios (Exp. 2) and hybrid (Exp. 4) output. These rank in descending order of P_m, as follows: the OCLI violet 2 ohm-cm cell with Corning 7940 coverslip and both AR coating and uv filter (Exp. 10); and the Spectrolab HESP cell with DC93-500 adhesively-bonded coverslip.

3. The FEP Teflon bonded "as-cut" quartz coverslip gives very high cell power output, with no evidence of any problems, and performs as well

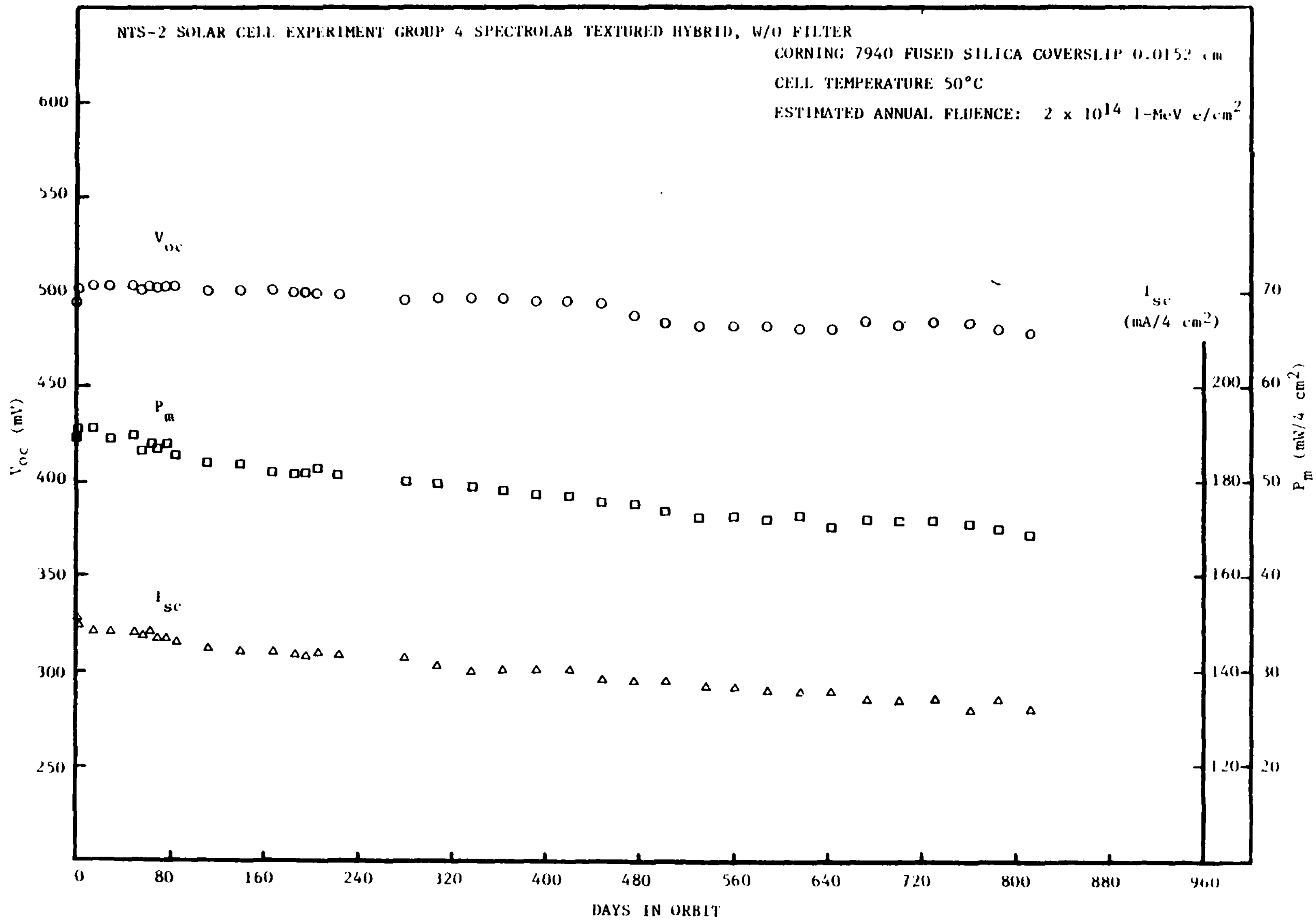

Figure 20 Degradation of P_m, I_{sc} and V_{oc} of the Spectrolab textured hybrid solar cell with FEP Teflon bonded coverslip. P_m and I_{sc} are normalized to 4 cm^2. (Experiment 4)

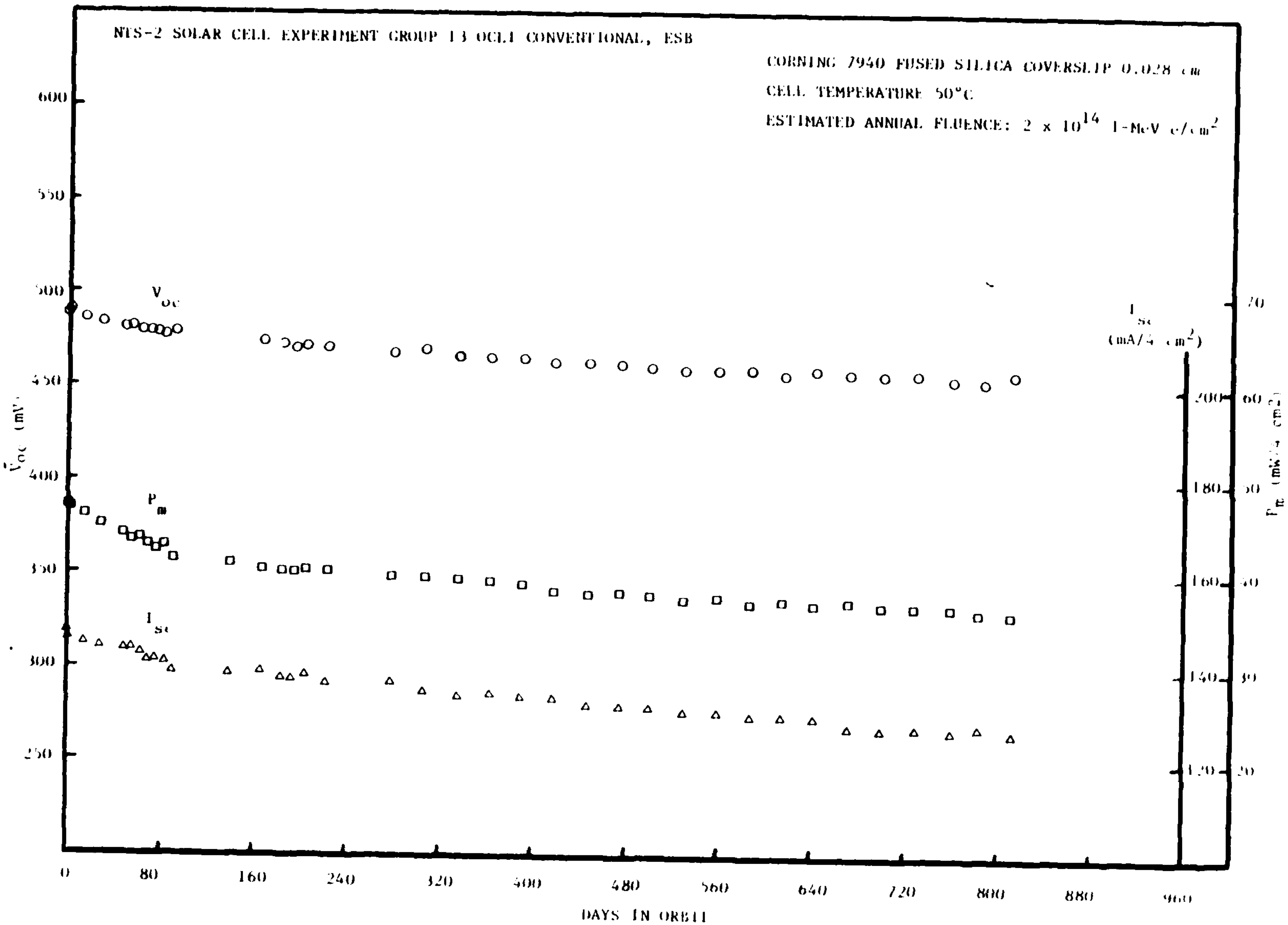

Figure 21 Degradation of P_m, I_{sc} and V_{oc} of the OCLI conventional solar cell with electrostatically bonded coverslip. P_m and I_{sc} are normalized to 4 cm^2. (Experiment 13)

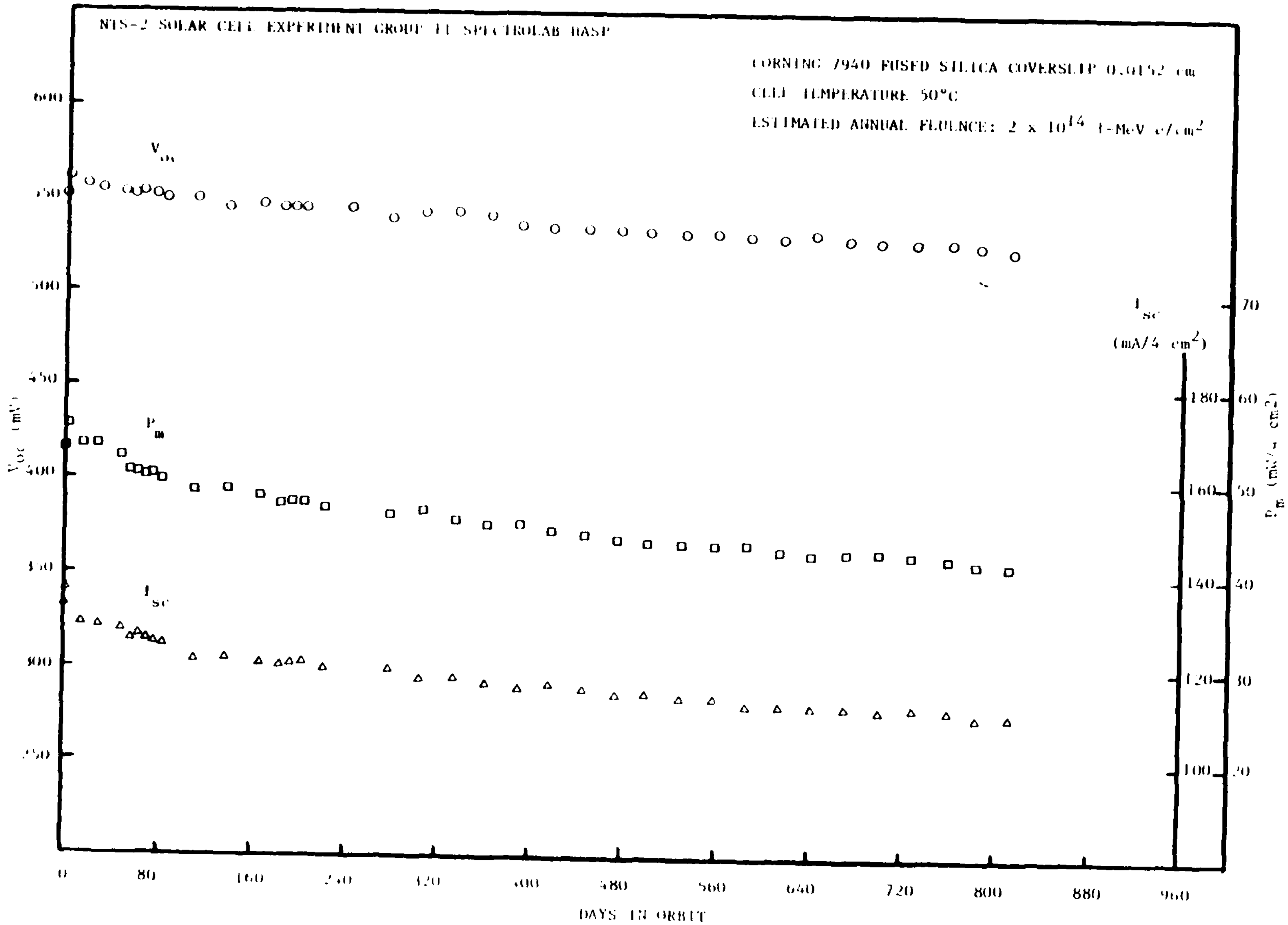

Figure 22 Degradation of P_m, I_{SC} and V_{OC} of the Spectrolab HASP cell (lithium-doped). (Experiment 11)

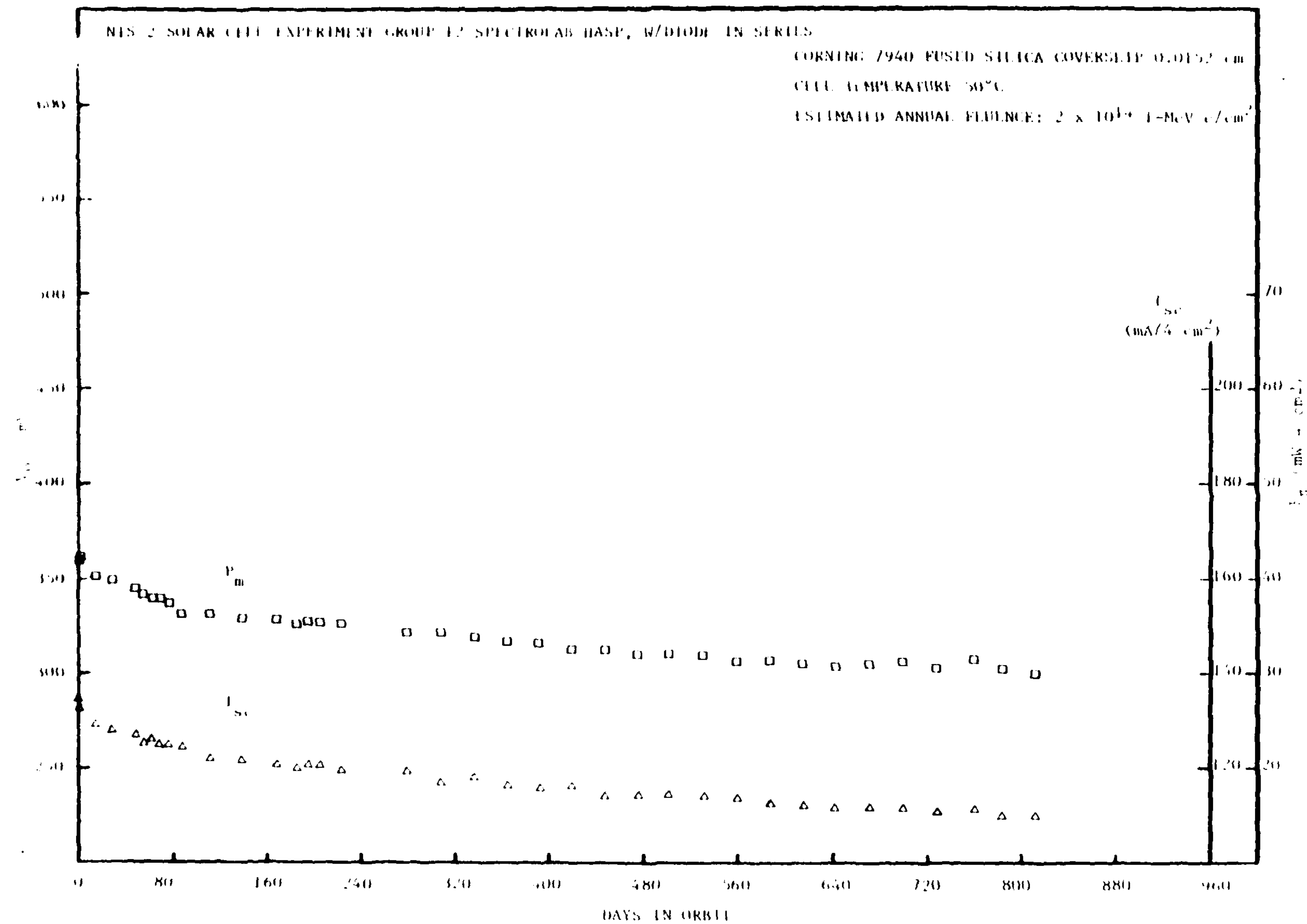

Figure 23 Degradation of P_m, I_{sc} and V_{oc} of the Spectrolab lithium-doped HASP solar cell in series with a planar diode. (*Experiment 12*)

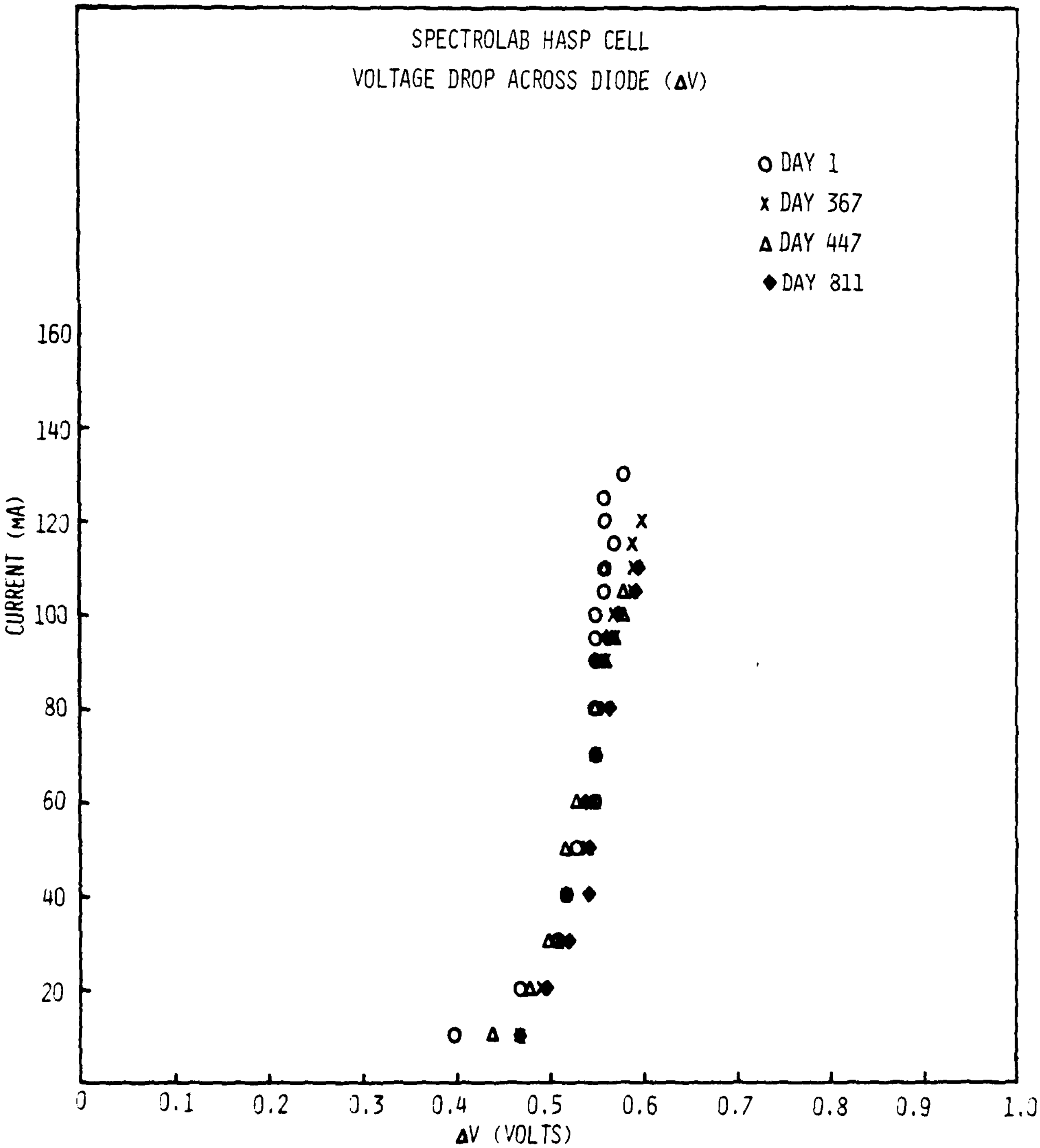

Figure 24 Comparison of changes in voltage drop across the diode in series with the Spectrolab lithium-doped HASP solar cell since day 1.

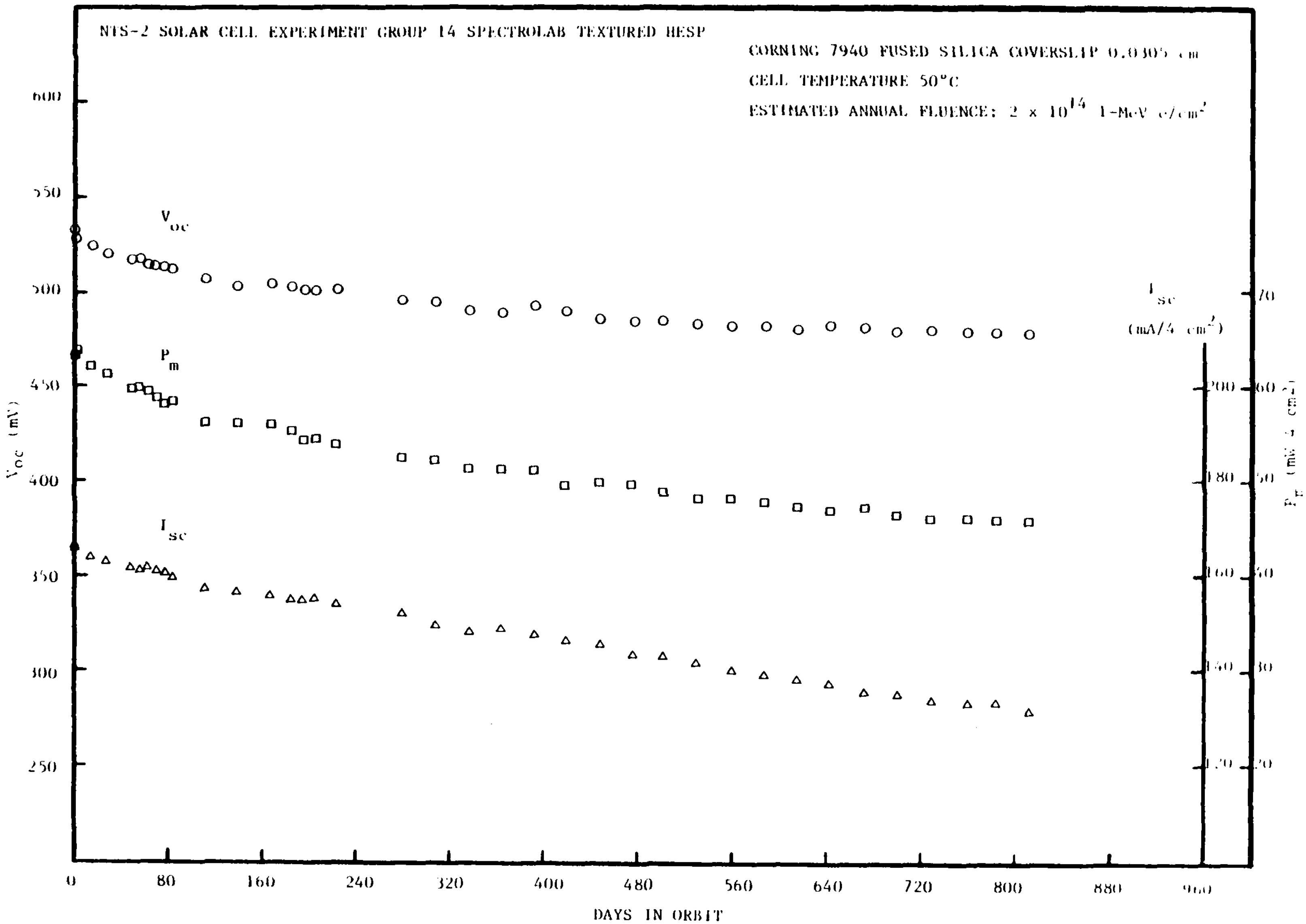

Figure 25 Degradation of P_m, I_{sc} and V_{oc} of the Spectrolab HESP solar cell. I_{sc} and P_m are normalized to 4 cm^2. (Experiment 14)

TABLE V
NTS-2 SHORT-CIRCUIT CURRENT OUTPUT FOR SOLAR CELL EXPERIMENTS

EXPERIMENT NO.	CELL TYPE	SHORT-CIRCUIT CURRENT OUTPUT (mA/4 cm^2)*			
		SOLAR SIMULATOR	DAY 1 IN ORBIT	DAY 811 IN ORBIT	% LOSS DAY 1 TO DAY 811
1	OCLI Conv. 2 ohm-cm	135.4	136.5	101.4	25.7
2	Spectrolab Helios (NTS-2)	154.5	155.5	122.5	21.2
3	Spectrolab Text. Hybr., F.S.	155.6	154.0	125.9	18.2
4	Spectrolab Text. Hybr., FEP, F.S. w/o filter	151.0	149.6	131.5	12.1
5	Comsat Text. F.S., w/o filter	184.8	180.4	97.7	45.8
6	Comsat Text. F.S.	180.8	178.7	136.6	23.6
7	Solarex Vert. Junc.	158.4	160.5	-	100
8	Solarex Space Cell	155.9	158.8	-	100
9	Spectrolab Text. Helios Reflector	174.3	175.8	-	100
10	OCLI Violet, F.S.	165.1	164.3	130.3	20.7
11	Spectrolab HASP w/o diode	136.2	132.6	110.2	16.9
12	Spectrolab HASP w/diode	134.5	132.4	110.0	16.9
13	OCLI Conv., ESB	147.3	146.1	126.5	13.4
14	Spectrolab HESP	166.2	165.8	131.3	20.8
15	HRL AlGaAs	102.9	100.6	75.4	25.0

*These data have been corrected to 50°C at one-sun and air mass zero (AMO).

Table VI
NTS-2 OPEN-CIRCUIT VOLTAGE OUTPUT FOR SOLAR CELL EXPERIMENTS*

EXPERIMENT NO.	CELL TYPE	SOLAR SIMULATOR	DAY 1 IN ORBIT	DAY 811 IN ORBIT	% LOSS DAY 1 TO DAY 811
1	OCLI Conv. 2 ohm-cm	533	549	512	6.7
2	Spectrolab Helios (NTS-2)	527	546	485	11.2
3	Spectrolab Text. Hybr., F.S.	491	508	480	5.5
4	Spectrolab Text. Hybr., FEP, F.S. w/o filter	491	505	478	5.3
5	Comsat Text. F.S., w/o filter	533	555	504	9.2
6	Comsat Text. F.S.	533	549	512	6.7
7	Solarex Vert. Junc.	528	521	-	100
8	Solarex Space Cell	535	541	-	100
9	Spectrolab Text. Helios Reflector	550	545	-	100
10	OCLI Violet, F.S.	550	552	525	4.9
11	Spectrolab HASP w/o diode	552	559	525	6.1
12	Spectrolab HASP w/diode	523	523	482	7.8
13	OCLI Conv., ESB	488	490	458	6.5
14	Spectrolab HESP	533	528	476	9.8
15	HRL AlGaAs	914	895	859	4.0

*These data have been corrected to 50°C at one-sun and air mass zero (AMO).

TABLE VII
NTS-2 SOLAR CELL EXPERIMENTS

SUMMARY OF CHANGES IN PHOTOVOLTAIC PARAMETERS*

		PERCENT LOSS DAY 1 TO DAY 811		
EXPERIMENT NO.	CELL TYPE	MAXIMUM POWER	SHORT-CIRCUIT CURRENT	OPEN-CIRCUIT VOLTAGE
1	OCLI Conv. 2 ohm-cm	31.6	25.7	6.7
2	Spectrolab Helios (NTS-2)	28.9	21.2	11.2
3	Spectrolab Text. Hybr., F.S.	25.2	18.2	5.5
4	Spectrolab Text. Hybr., FEP, F.S. w/o filter	20.6	12.1	5.3
5	Comsat Text. F.S., w/o filter	52.1	45.8	9.2
6	Comsat Text. F.S.	27.8	23.6	6.7
7	Solarex Vert. Junc.	100	100	100
8	Solarex Space Cell	100	100	100
9	Spectrolab Text. Helios Reflector	100	100	100
10	OCLI Violet, F.S.	25.7	20.7	4.9
11	Spectrolab HASP w/o diode	26.0	16.9	6.1
12	Spectrolab HASP w/diode	28.7	16.9	7.8
13	OCLI Conv., ESB	23.1	13.4	6.5
14	Spectrolab HESP	28.2	20.8	9.8
15	HRL AlGaAs	24.8	25.0	4.0

*These data have been corrected to 50°C at one-sun and air mass zero (AMO).

as or better than adhesively-bonded uv filter Corning 7940 for radiation shielding and optical transmission.

4. The Hughes gallium-arsenide cell has the smallest degradation rate for V_{OC} of all cells.

Some unresolved questions which are of great importance and deserve further investigation are:

1. The annealing of V_{OC} and P_m in the gallium-arsenide cell during the first 80 days.

2. Thermal cycling effects in the vertical junction solar cell.

3. Unexpectedly large I_{SC} loss in a solar cell covered with adhesively-bonded Corning 7940 coverslip having no uv filter to protect against uv darkening of the adhesive.

Acknowledgments

The author expresses appreciation to R. L. Statler for suggestions and assistance, to Dr. B. J. Faraday, Head of the Radiation Effects Branch, to J. Wise, Air Force Aero Propulsion Laboratory and to CAPT R. Widby, Space Division, Air Force Systems Command, for their continual support; and to R. J. Lambert of the Satellite Components Section for his help with the data reduction.

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